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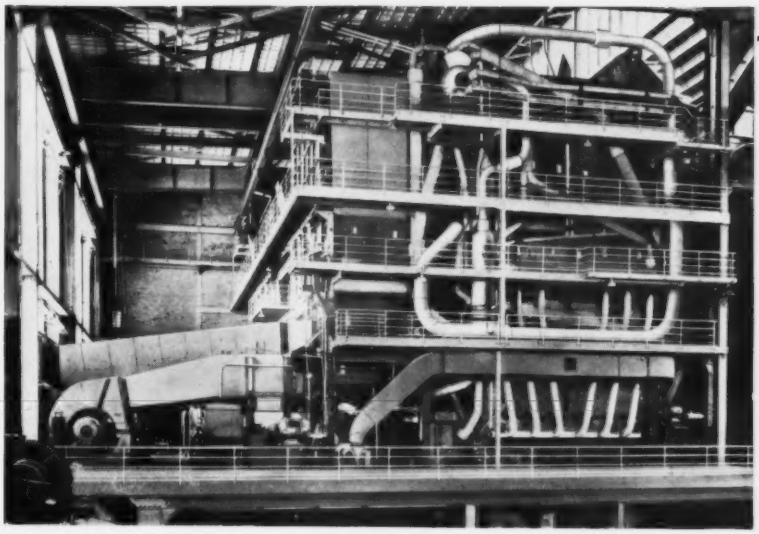

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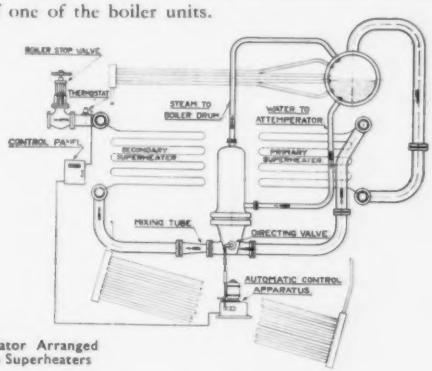

Attemperator Arranged between Superheaters

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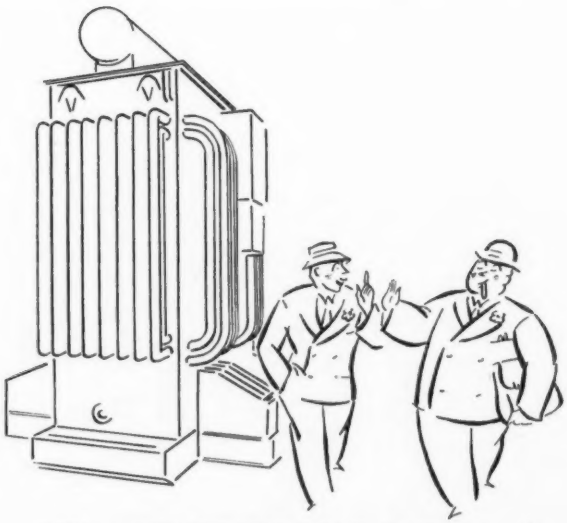

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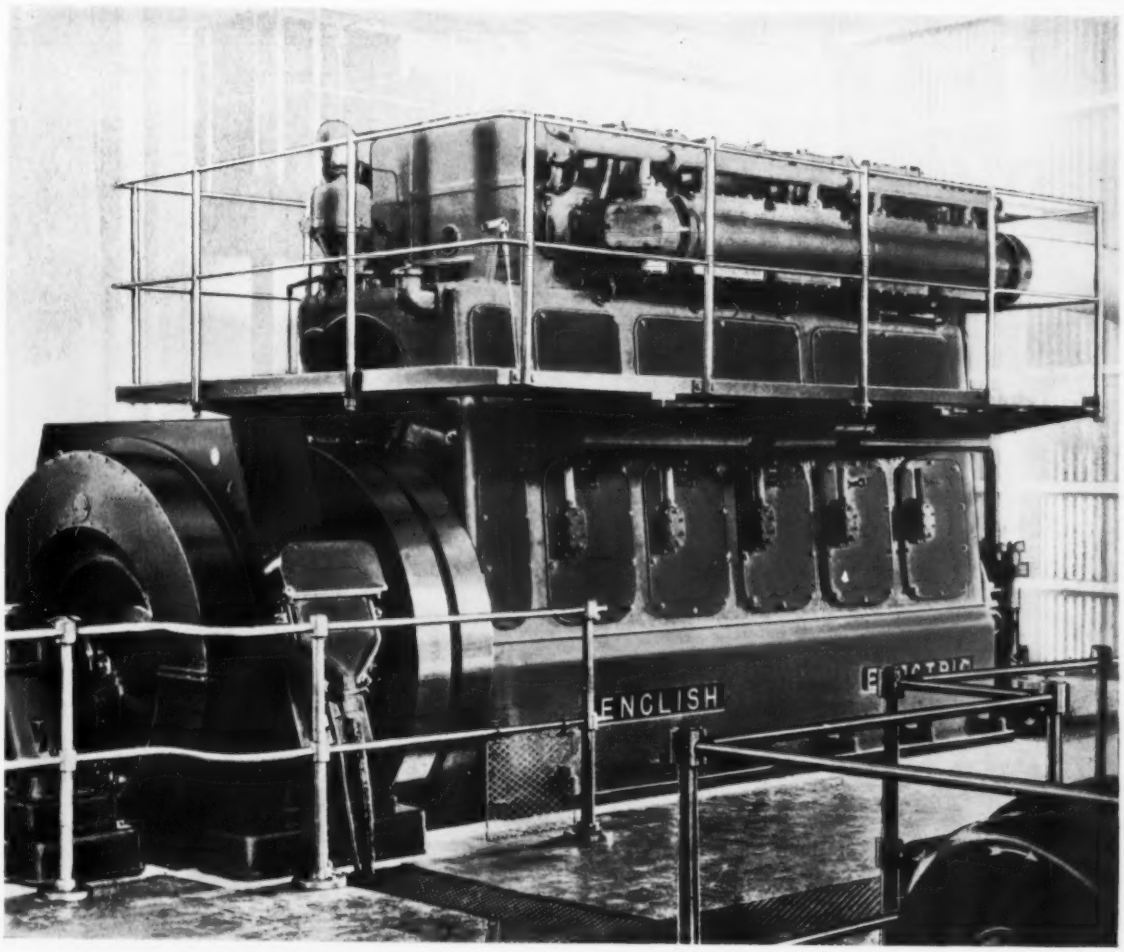

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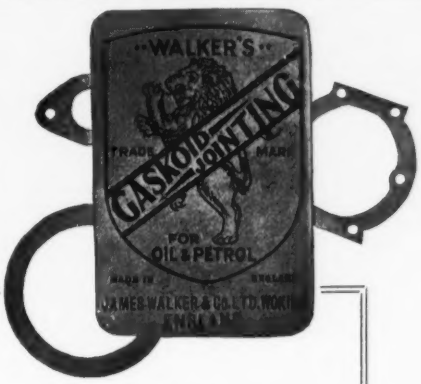

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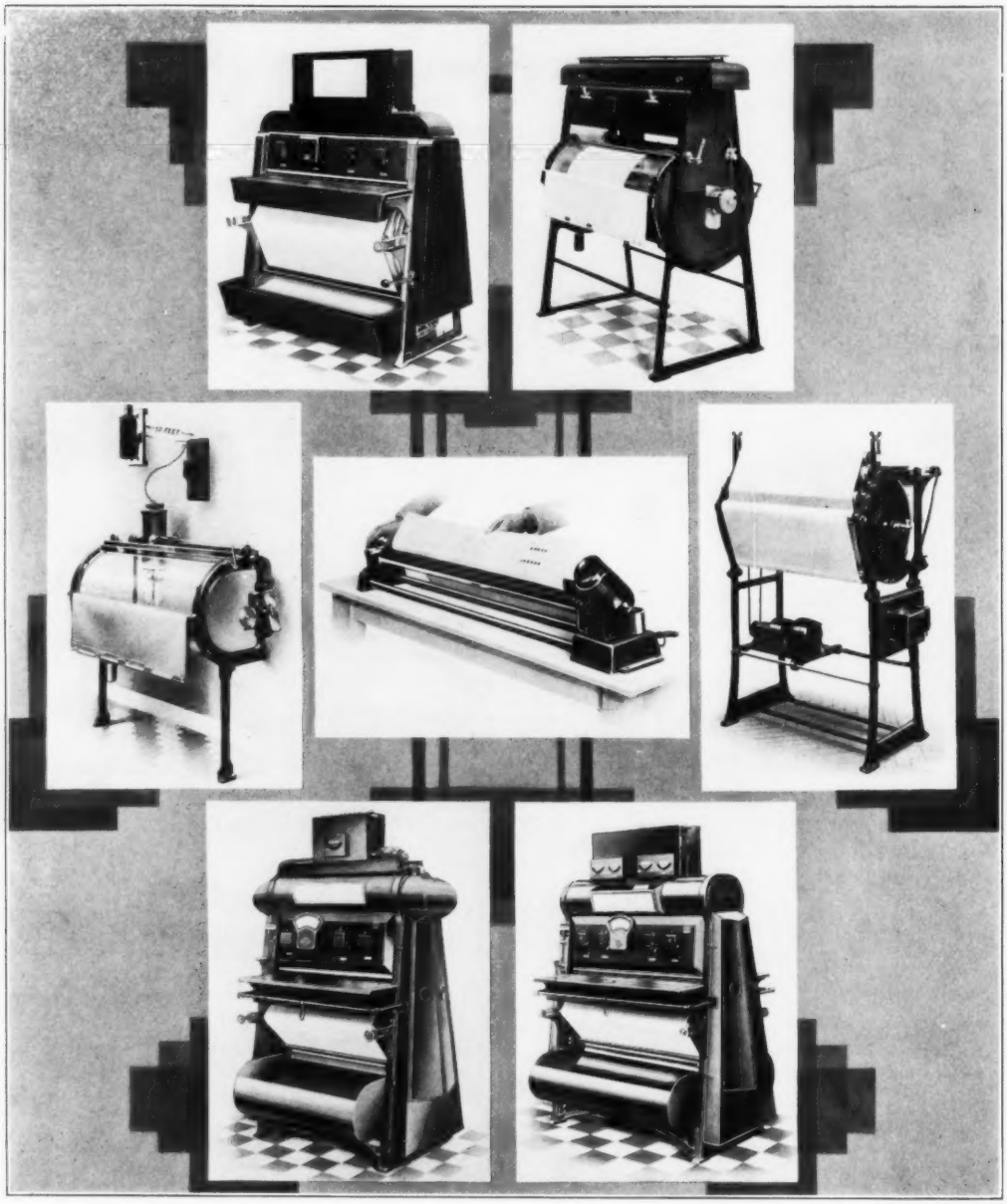

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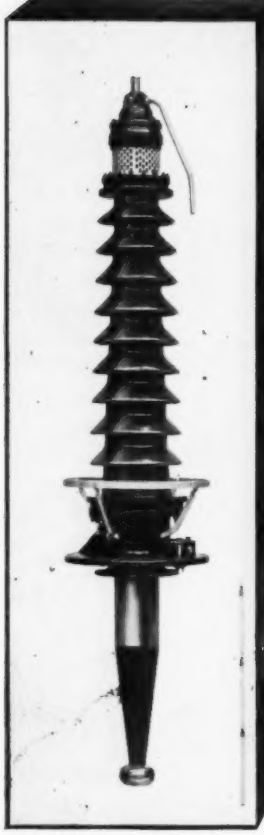
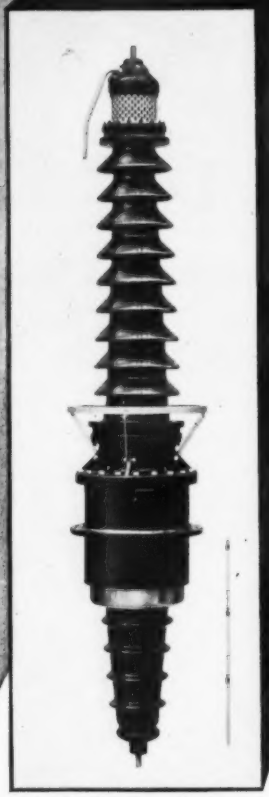
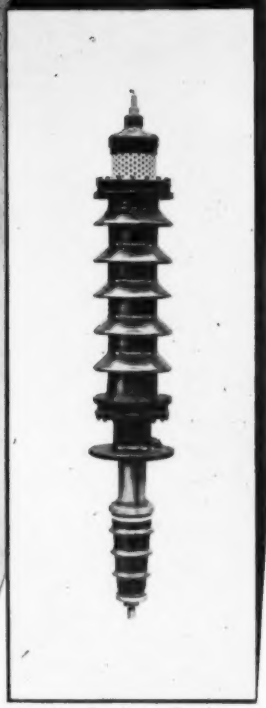


154 kV. Outdoor Condenser Type Transformer Bushing (Oil Filled).



154 kV. Outdoor Condenser Type Oil Circuit Breaker Bushing (Oil Filled).



66 kV. Outdoor Condenser Type Oil Circuit Breaker Bushing (Oil Filled).

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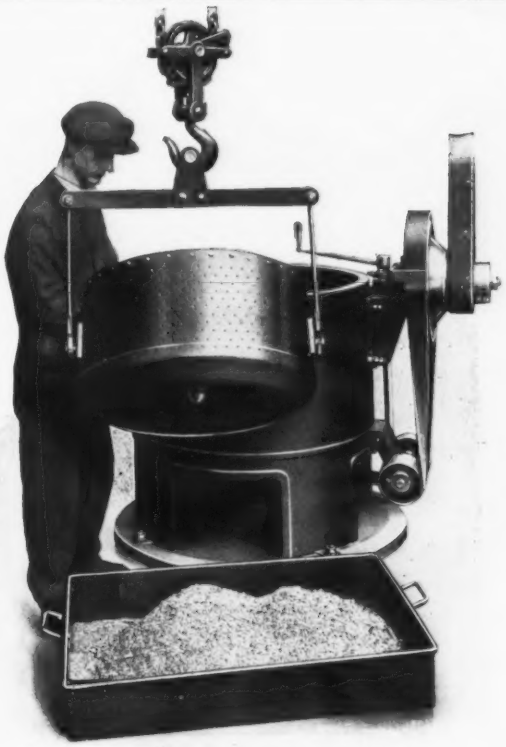

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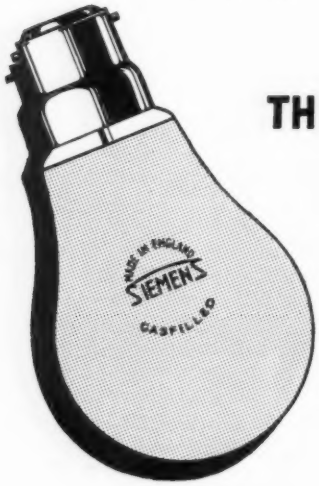

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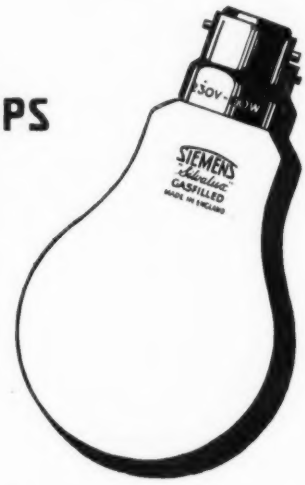

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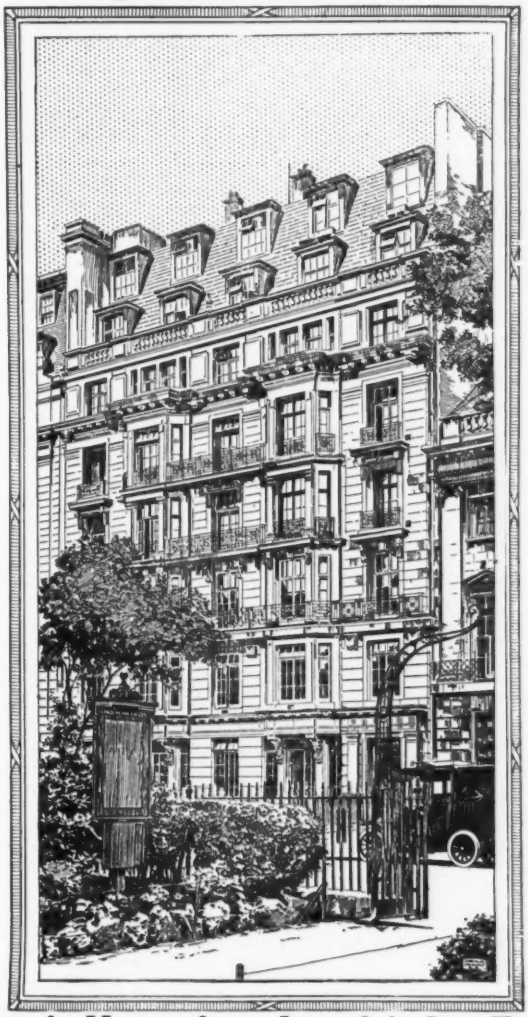

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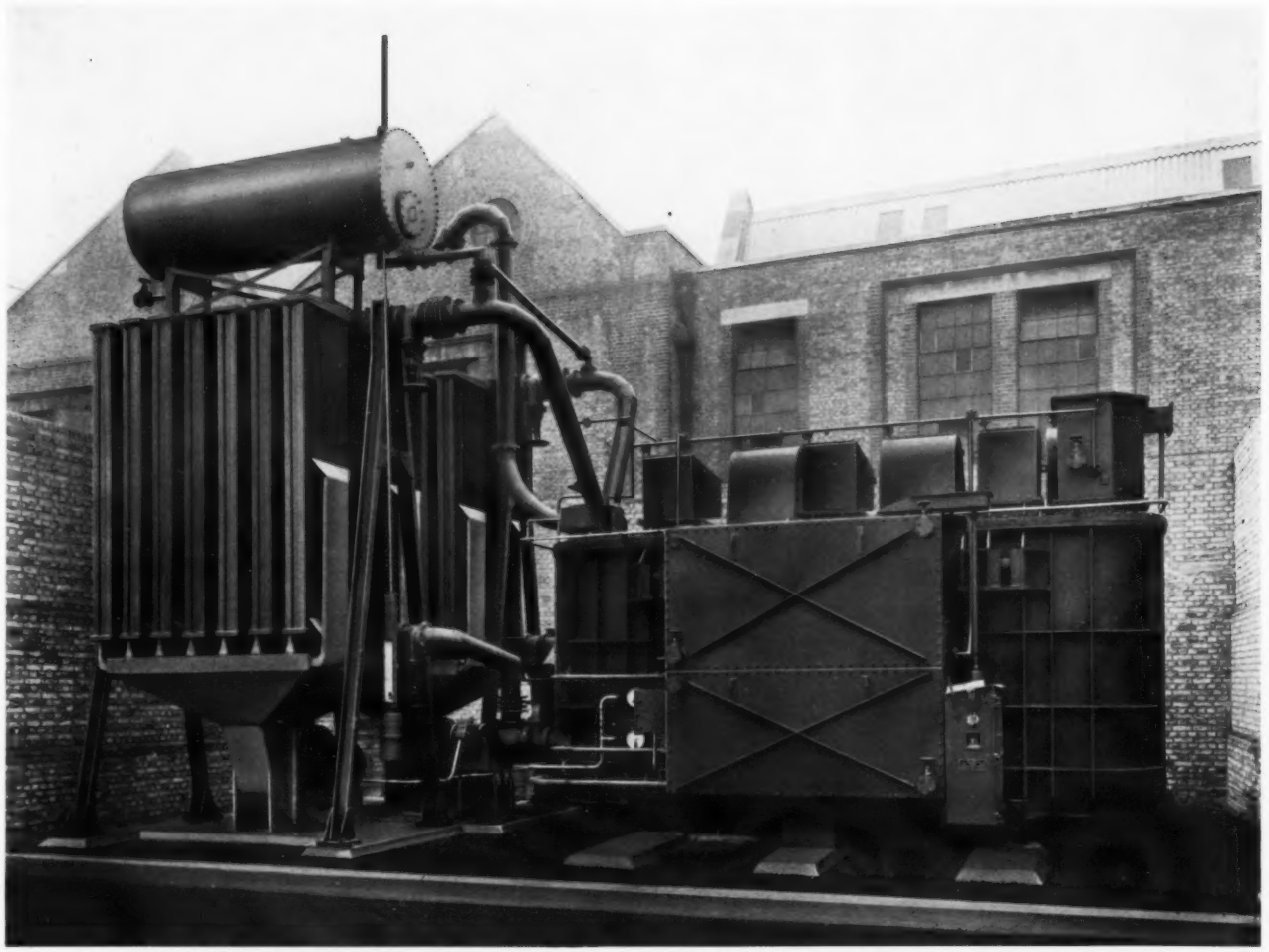

One of the 45 mV.A. Transformers at the Fulham Transforming Station of the Central Electricity Board.

The English Electric Journal

Vol. VIII. No. 4 DECEMBER, 1936 One Shilling.

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All Communications respecting Editorial Contents should be addressed to THE EDITOR, THE ENGLISH ELECTRIC JOURNAL, THE ENGLISH ELECTRIC COMPANY LIMITED, STAFFORD.

EDITORIAL.

In the first article of this issue Mr. A. M. Pooley describes the Company's high-rupturing capacity cartridge fuse and outlines its applications for the protection of industrial and substation distribution equipment. On account of its high rupturing capacity and high speed of rupture, this fuse is eminently suitable for the short-circuit protection of motor circuits and for the back-up protection of low-tension and high-tension circuit breakers. Other applications described and illustrated include distribution boards and "Combination" fuse-switch equipment for industrial use, and the Company's recently introduced overhead busbar chamber distribution system for individually driven machine tools. Substation gear of the "Skeltag" and "U.35" types is also described and the recently developed low-tension pole-mounting ground-operated rural distribution fuse fitting type R.D.J. is introduced.

In the next article Mr. G. T. Shoosmith describes the four-coach articulated Diesel-electric trains which the Company

have under construction for the Ceylon Government Railways. The experience gained by the Company with the original Diesel-electric rail coach (described in Vol. VI, No. 7) has been of great value in the design of the power equipment and mechanical parts of the Ceylon trains. It is noteworthy that the complete trains, including Diesel engines, electrical equipment, mechanical parts and bodies have been designed and manufactured throughout in the Company's own works. We believe that the Company hold in this respect a unique position in Great Britain.

Scientific Developments in Transformer Construction, by Mr. R. M. Charley, is continued in the third article. Two recent transformer installations are described and illustrated. The first section of the article describes the 45 mV.A. transformers supplied by the Company for the Central Electricity Board's transforming station at the Fulham Power Station. The Fulham 66 kV. Busbar is coupled to the 132 kV. Grid at Willesden through these transformers. On-load tap-changing gear is provided on the 132 kV. side. The second section of the article describes the transformers supplied to the Victoria Falls and Transvaal Power Co., Ltd., South Africa. The transformers are single-phase units, three units being connected to form a three-phase bank of 55 mV.A. capacity. The voltage ratio of the transformers is 76/42 kV. On-load tap-changing gear is provided on the H.V. side.

In the concluding article of this number we reprint from "Engineering" an article on The Determination of Turbine Disc Stresses by Mr. S. J. E. Moyes. This article will, we think, appeal to those of our readers who are interested in the design of steam turbines.

Important Contract for Turbo-Alternator Plant.

In order to cope with the continually increasing demands for electricity, the Yorkshire Electric Power Company are making large extensions to their Ferrybridge Power Station. They have recently awarded a contract to the Company for two 40,000-kW. steam Turbo-Alternator Sets running at 3,000 r.p.m. It is noteworthy that these machines are the first of this output and speed to be ordered for use in this country; their adoption is in accordance with the policy of the Yorkshire Electric Power Company to take advantage of all the latest engineering developments so as to obtain the most economical results; they were among the first to take advantage of the English Electric Company's pioneering development of 3,000 r.p.m. Multi-Cylinder 30,000 to 40,000 kW. Turbines and their foresight in installing these machines together with high efficiency boilers has resulted in their generating costs being as low as any in the country.

British Industries Fair, Birmingham. February 15th to February 26th, 1937.

A cordial invitation is extended to all our readers to visit the Company's stand, No. Cb 609, in the Electrical Section of the Fair. Exhibits will include a wide range of industrial fuse gear, domestic, heating and cooking appliances, including electric fires, cookers, water heaters, washing machines, irons; and fractional horse-power motors.

The High Rupturing Capacity Cartridge Fuse, Design and Applications.

By A. M. POOLEY, M.B.E., Manager, Fusegear Section.

In recent years the attention which has been concentrated on the design of fuses has led to the marketing of a high rupturing capacity fuse which is a highly accurate and reliable piece of apparatus.

The first essential of such a fuse is that it shall be capable of satisfactorily clearing a short circuit of the maximum severity obtainable in the system on which it operates. This in itself is not a difficult problem. There are, however, other essential conditions to be fulfilled which are not always realised by the user. The fuse must carry full-load current indefinitely without deterioration; the temperature rise under full-load conditions must be of a low order and, under overload conditions, it must be impossible for the fuse to reach such a temperature that it will injure the contacts or cable connections. The speed of rupture should be high to minimise the arc energy and be accompanied by low voltage rise; and the fuse should operate silently without visible disturbance.

The open wire fuse deteriorates rapidly when run at or near its rated normal carrying current, and in many other respects it is unsatisfactory. As an alternative the straight wire fuse can be enclosed in a sealed casing filled with an arc-quenching material. This form of construction may give high rupturing capacity, but invariably it is accompanied by a severe voltage surge when interrupting a short circuit and has a high temperature rise under full-load conditions. It is suitable only for fuses of low rating.

The essential conditions are completely met by the "English Electric" high rupturing capacity fuse, which incorporates a fabricated silver element (design patented), as shown in Fig. 1, the rating being determined by the diameter and length of the central wire. The strengthened end-connections and the loops on the multi-break type reduce the resistance considerably, thus enabling a fuse to be produced which has a low temperature rise. The left-hand illustration, Fig. 1, shows the single-break type of element as used for the low tension fuse having a rupturing capacity of 25,000 kVA. at 440 volts, 3-phase, with a fuse in each conductor. For low-tension fuses requiring a higher rupturing capacity, a double-break element is used, which will be referred to later in this article.

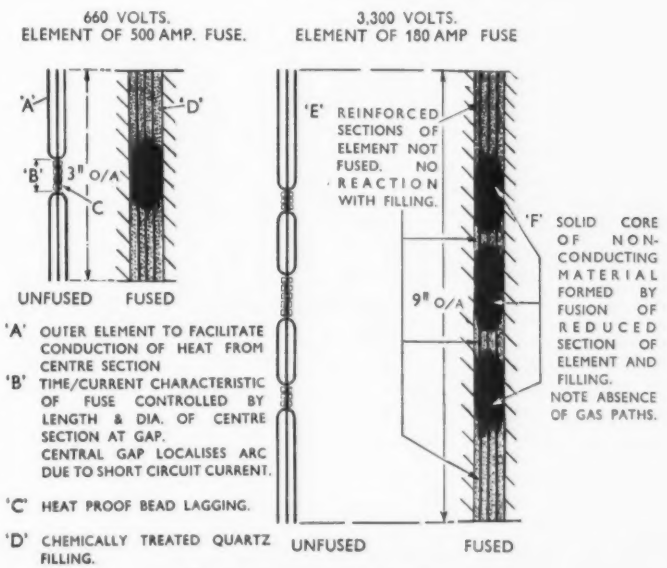

660 VOLTS.
ELEMENT OF 500 AMP. FUSE.
3,300 VOLTS.
ELEMENT OF 180 AMP FUSE
'A'
'B'
3" O/A
'C'
'D'
UNFUSED
FUSED
'A' OUTER ELEMENT TO FACILITATE CONDUCTION OF HEAT FROM CENTRE SECTION
'B' TIME/CURRENT CHARACTERISTIC OF FUSE CONTROLLED BY LENGTH & DIA. OF CENTRE SECTION AT GAP. CENTRAL GAP LOCALISES ARC DUE TO SHORT CIRCUIT CURRENT.
'C' HEAT PROOF BEAD LAGGING.
'D' CHEMICALLY TREATED QUARTZ FILLING.
'E' REINFORCED SECTIONS OF ELEMENT NOT FUSED. NO REACTION WITH FILLING.
9" O/A
'F' SOLID CORE OF NON-CONDUCTING MATERIAL FORMED BY FUSION OF REDUCED SECTION OF ELEMENT AND FILLING. NOTE ABSENCE OF GAS PATHS.
UNFUSED
FUSED

Fig. 1.—Patented Fusible Element.

Generally speaking, each element has a rating not exceeding 30 amps.; thus a 300-amp. fuse has 10 such elements. These elements are enclosed in a ceramic body, which, for fuses rated over 100 amps., is of the multi-chamber construction to prevent interaction between the elements, each chamber accommodating two elements.

The elements are secured to the inner end-caps, and the chambers are first completely filled with a graded and treated quartz filling and then are sealed with porcelain plugs, which are cemented in position. The outer metal end-caps carrying the contacts are pressed on and, finally, the inner and outer caps are soldered together.

The multi-break element, as shown on the right-hand side of Fig. 1, is the type used in the 3,000-volt fuse which is available in all ratings up to 180 amps., and has a rupturing capacity of 150,000 kVA.

It will be appreciated that with the patented type of fuse, only that portion of the element comprising the single-wire section is volatilised, and the relatively long triplicated sections of the fuse element at each side of the centre section remain intact. The length of the fuse is greater than that which is necessary to provide the required rupturing capacity, but is, however, controlled by the necessity of having a satisfactory flash-over distance between end-caps, and to enable the design to incorporate side indication to show when the fuse has blown. The length of the standard 25,000 kVA. fuse body is sufficient to enable a double-break element to be used, which gives a greatly increased rupturing capacity.

A series of short-circuit tests have conclusively proved that the double-break element, as compared with the single-break element, reduces by 35 per cent. the arc energy with which the fuse has to deal. Further, the heat generated by the short circuit, instead of being centred at one point, is dealt with at two separate points, and the corresponding body strains caused by the sudden temperature rise are thereby greatly reduced. Fig. 2 shows two typical short-circuit test results, the physical dimensions in both cases being those of a standard 60-amp. fuse.

The Company's fuse has a remarkably high speed of rupture, and this can best be appreciated by a comparison of the results of short-circuits cleared by fuses and by circuit-breakers. Many tests which have been carried out under exactly similar conditions illustrate the point in a clear manner.

Fig. 3 shows a composite record of short-circuit D.C. tests, the power being supplied by a battery of 4,000 ampere-hour cells with an open circuit P.D. of 400 volts, and the prospective current value for the circuit being not less than 35,000 amps. The chain-dotted line is the record of an "English Electric" "T" type, 500-amp. fuse, and the solid line shows the record of an air circuit-breaker with the time lags removed. The record of the fuse test shows very clearly how the reduced section of the element produces an extremely short pre-arcing time .01 sec., thus

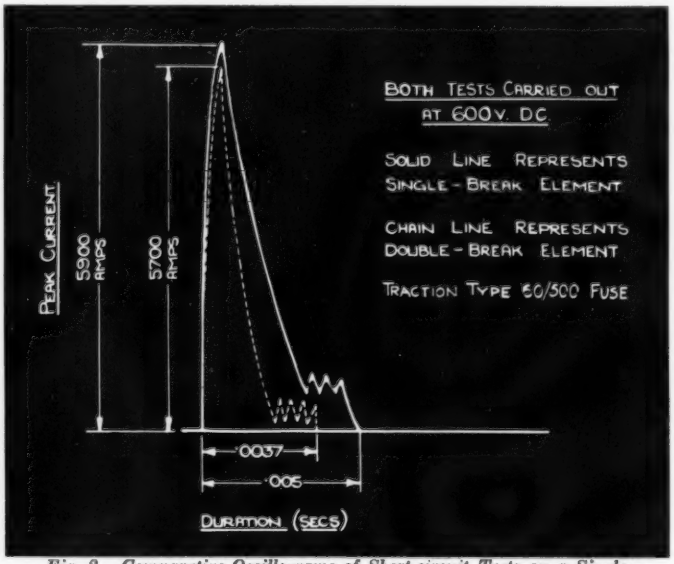


Fig. 2.—Comparative Oscillograms of Short-circuit Tests on a Single and Double-break Element.

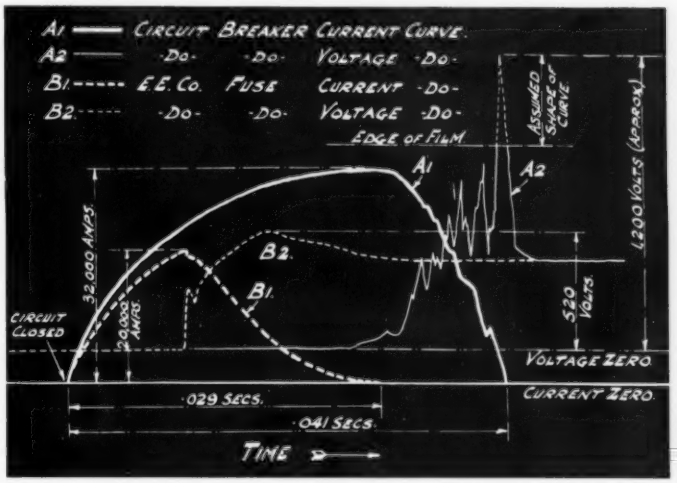


Fig. 3.—Comparative Oscillograms of Short-circuit Tests on an "English Electric" High Rupturing Capacity Fuse and a Circuit Breaker.

reducing the amount of current flowing into the fault. Immediately after the centre section has volatilised, the interaction with the quartz filling commences to insert resistance, the value of which increases until the current reaches zero. Thus, as shown on the oscillogram, a relatively lengthy arcing time, .019 sec., is obtained, which, by virtue of the reduced rate of current decrement, keeps the voltage rise within permissible limits.

Comparison of the two curves shows that the pre-arcing time for the fuse is .01 sec., as against .029 sec. for the circuit-breaker, and that the fuse has the relatively lengthy arcing time of .019 sec., as against that of the circuit-breaker —.012 sec. The average rate of decrease of amperes during the arcing period of the fuse is 1,050 amps. per milli-second, whereas with the circuit-breaker the current change is equal to 2,670 amps. per milli-second. This rapid rate of current change of the circuit-breaker causes a voltage surge having a peak value of 3 times normal, whereas in the case of the fuse the volts do not exceed normal by more than 30 per cent. It is interesting to note that the fuse limited the current rise to 20,000 amps., whereas the prospective current value, as already stated, was not less than 35,000 amps.

Discriminating Performance.

Discrimination by fuses is of particular value in distribution networks, and this property of the Company's fuse has definitely been established by two sets of short-circuit tests recently carried out on the range of "J" type fuses.

In the first set the system prospective current exceeded 33,000 amps. and perfect discrimination was obtained when a range of fuses with ratings varying in steps of 100 amps. was tested, the larger fuses in each case remaining intact.

In the second set of tests the current was limited to 3,000 amps. approximately, and when the whole range of fuses was tested, in every case discrimination in steps of 50 amps. was obtained.

Application of the English Electric High Rupturing Capacity Fuse.

Short-Circuit Protection of Motor Circuits.

In many industrial plants to-day it is possible to obtain a fault kVA. well in excess of that which safely can be interrupted by the motor control gear, and one of the most important functions of the high rupturing capacity fuse is to provide short-circuit protection and relieve the control gear of that duty.

The "English Electric" high rupturing capacity fuse is eminently suitable for this purpose by virtue of its extremely high rupturing speed, which, under short-circuit conditions, enables it to operate well in advance of the control gear and so prevent damage to the gear and contacts. The Company's fuses have a fusing time on short-circuit of less than one-eighth of that of the standard over-current trip and discrimination is readily obtained.

Fig. 4 shows how a 30-amp. "English Electric" fuse provides short-circuit protection for a 10 h.p. squirrel-cage direct-on start motor on a 500-volt, 3-phase supply. The over-current

trips take care of those conditions under which the current does not exceed 80 amps., or a peak starting value of seven times the full-load current for a period up to 10 seconds, while the fuse operates under conditions of greater severity.

Back-up Protection.

Another application of high rupturing capacity fuses is to the back-up protection of low rupturing capacity low-tension and high-tension circuit-breakers. The speed of rupture of the fuse being higher than that of the circuit-breaker enables the fuse to clear a severe short-circuit before the circuit-breaker has time to operate, the latter remaining in the circuit for the purpose of opening and closing the circuit and for providing protection against overloads.

In many cases the circuit-breakers have a rupturing capacity which, at the time of their installation, was quite adequate to meet the heaviest duty imposed upon them, but which is inadequate to meet new supply conditions. The cost of replacing the switches with switches of adequate rupturing capacity is often very great, and a more economical solution is to install high rupturing capacity fuses to provide the necessary short-circuit protection.

Where the low rupturing capacity switchgear is so equipped and the switches have been grouped to obtain discrimination, this can in general be reproduced by suitably grading the fuse ratings.

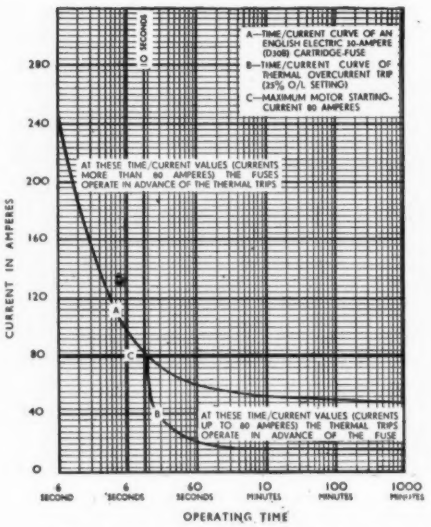


Fig. 4.—Overcurrent and Short-circuit Protection on a 10 h.p., 3-phase, 500-volt Motor.

Fig. 5 shows part of a low-tension switchboard fitted with switches having a low rupturing capacity, short-circuit protection being provided by "English Electric" high rupturing capacity fuses, whilst the switches remain in circuit to provide overload protection and to open and close the circuit.

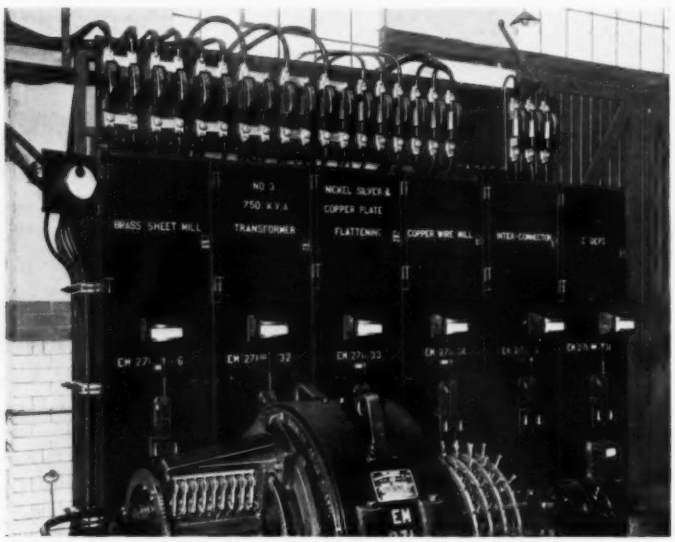


Fig. 5.—Circuit-breaker Board with protection by High Rupturing Capacity Fuse Cartridges.

It will be seen from the illustration (Fig. 5) that two fuses are used in parallel in order to deal with the working load, which is over 1,200 amps.

"English Electric" high-tension fuses of 180 amps. rating at 3,300 volts have recently been installed to provide back-up protection to a number of low rupturing capacity high-tension oil circuit-breakers in a large steelworks. The fuses are installed in series with the circuit

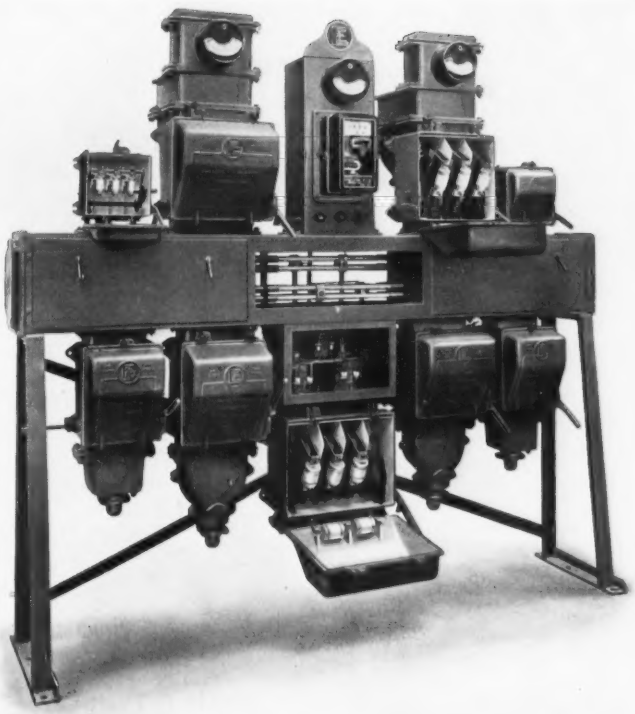


Fig. 6.—Combination Fuse-switch Board with Metering Equipment.

breakers and are giving satisfactory performance under conditions where the short-circuit fault capacity exceeds 125,000 kVA.

Factory Distribution.

The " Combination " fuse-switch is a compact arrangement of double-break switch and fuses wherein the fuses form links in the switch blades. The switch unit is designed for assembly either above or below a central busbar chamber and by the use of links instead of fuse cartridges, the units may be used as isolators. The fuse-switch is available in any arrangement from single-phase to 3-phase and neutral or 4-pole, and in its design ample attention has been paid to the provision of rapid cabling facilities. Cabling is further simplified by the double-break action which allows both incoming and outgoing connections to be taken direct to the fuse-switch contact blocks. " Combination " fuse-switches are available for floor and wall mounting in four ratings—30, 60, 150 and 300 amps. Fig. 6 shows a typical " Combination " fuse-switch board.

Metal-clad Distribution Boards.

Metal-clad Distribution Boards are available in all ratings up to 800 amps. All sizes comply with Home Office Regulations and incorporate the " English Electric " high rupturing capacity cartridge fuse. These boards are constructed on robust lines to enable them to withstand the most arduous operating conditions, and their design affords simplified cabling facilities. The fuse bases of boards up to 150 amps. rating are rotatable around the busbars, and the use of reversible cable sockets enables cabling to be effected very rapidly.

Immediate localisation of blown fuses is

Fig. 7.—Typical Overhead Busbar Chamber Distribution Installation in a Motor Works.

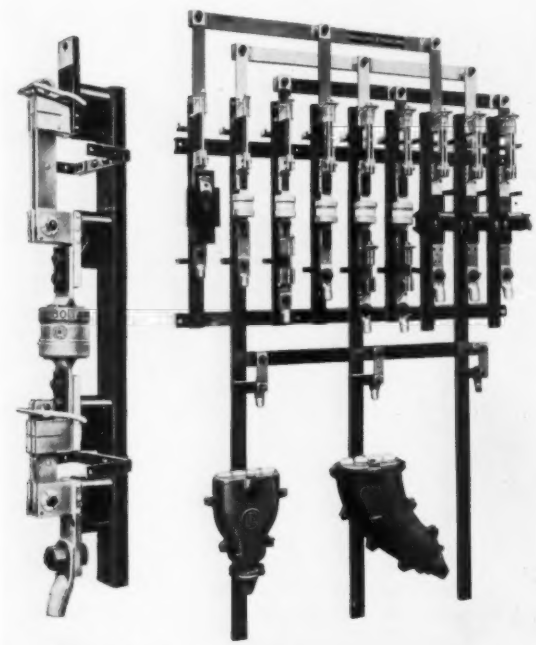


Fig. 8.—"Skeltag" Gear, incorporating Tag-end Fuses.

obtained by the use of front indicating handles on all sizes.

The Overhead Busbar Chamber System.

The Overhead Busbar Chamber System has been designed for factory distribution to individually driven machine tools and to permit modifications to machine shop layouts to be carried out without altering the main distribution layout or interfering with the supply to existing machines. The basis of the system is a standard 12 ft. unit consisting of insulated busbars housed in a metal-clad chamber, which is erected overhead and which can readily be built up on site to suit any particular distribution arrangement or machine tool layout, cleats around the roof truss ties providing a satisfactory rigid fixing. Each 12 ft. length of busbar chamber is provided with 6 or 9 tapping sockets, which accommodate plug-in metal-clad fuse units from which power is taken direct to the machine tools below through either conduit and cable or flexible

armoured cable. These units incorporate the Company's high rupturing capacity fuse of 30 amps. or 60 amps. maximum rating, and the pins and sockets are so arranged that insertion or withdrawal of the units can be effected whilst the system is alive and without interfering with the supply to adjacent machines.

Figure 7 shows a typical overhead busbar installation in a motor car works and the neatness of the arrangement and the absence of interference with the lighting and other equipment will particularly be noted.

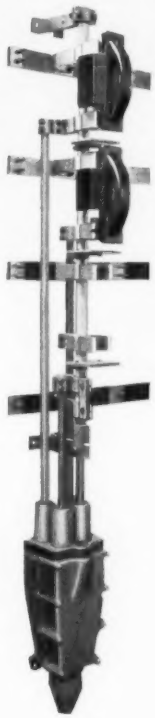


Fig. 9.
Universal Unit, Type U.35.

Substation Distribution.

The "Skeltag" Distribution Gear employing the bolted-on tag-end fuse is a development of the skeleton gear employing the now obsolescent dome-end fuse. Fig. 8 shows a composite "Skeltag" board and illustrates single and double isolator fused units and incoming transformer units with metering equipment. The units, which are available in ratings of 500 amps. and 800 amps., are wall-mounted and all the components are accessible from the front.

The "U.35" Distribution Unit is a development of the Universal distribution unit, designed to afford improved facilities for cabling-up. A vertically split dividing box and interchangeable cable sweating sockets enable connections to be carried out in a direct manner and avoid the necessity for crossing the cable cores when phasing out. "U.35" units are made in three ratings, 300, 500 and 800 amps., all three sizes being interchangeable. Fig. 9 illustrates a typical unit.

Fig. 10.
Pole-operated Fuse Unit, Type R.D.J.

Rural Distribution.

As an addition to the Company's pole-mounting, ground-operated rural distribution fuse gear, a low-tension fitting which can be fused up to 160 amps. has been developed and is of similar general construction to the 11,000-volt unit, type R.D.

This low-tension fitting type R.D.J., shown in Fig. 10, is provided with a self-contained supporting bracket, which allows its erection on any part of the pole to suit any particular arrangement of conductors. The dome end cartridge fuse is employed and the same operating socket can be used for inserting and withdrawing both low-tension and high-tension fuses.

Diesel Traction Progress.

By G. T. SHOOSMITH, M.A.

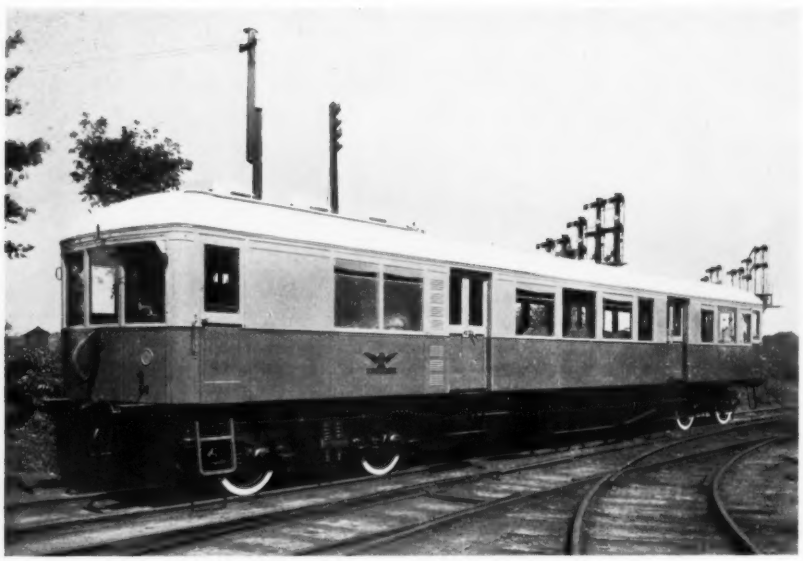


Fig 1.—200 h.p. "English Electric" Diesel-electric Rail Coach.

In previous articles, published in the December, 1933, and January, 1935, issues of this Journal, the Company's Diesel-electric Rail Coach and Shunting Locomotives were described. These related to developments undertaken by the Company during years of comparative depression, and it is therefore interesting to survey at the present time the results which have been obtained. It is proposed to deal in this article with the railcar field and to describe briefly the trains now under construction for the Ceylon Government Railways. A subsequent article will review the Diesel locomotives recently completed and under construction.

In May, 1936, the Company received an order, through the Crown Agents for the Colonies, for three 4-coach articulated diesel-electric trains for service on the Ceylon Government Railways, on a route of approximately 100 miles between Colombo and Matara. The first section of the route running from Colombo is a thickly populated suburban area with stations at close intervals. The latter section is more thinly populated, and the whole route runs roughly parallel with the sea coast. The area is served by good roads on which considerable private car and bus competition has to be met. As a result of the increased comfort and modern appearance of the new train units, it is hoped to regain much of the traffic that has been lost to the road and, at the same time, to reduce operating costs while increasing revenue.

The new trains will be the first multi-coach, streamlined, lightweight, diesel units of their type yet built in this country and will, in appearance and performance, be the equal of any similar units constructed abroad. The design is the result of an exhaustive study of foreign makes of

railcars and diesel train units, including visits by the Company's engineers to many continental railways operating such stock.

The experience gained by the Company with the original Diesel-electric rail coach illustrated in Fig. 1, and which, by the courtesy of the L. M. & S. Railway, was operated on their lines for over two years, has been of paramount importance in the design of the Ceylon trains, both as regards the power equipment and the mechanical parts of the coaches themselves.

The outline and general arrangement of the Ceylon trains are given in Plate I, from which it will be seen that a pleasing streamline effect has been obtained without excessive front overhang. The articulated coaches are connected by bellows, thus preserving the general body-contour and reducing wind resistance. To assist this same purpose the body panels are continued below the floor level in the form of skirtings, which are arranged for easy removal where necessary for attention to the bogies and running gear.

The total seating capacity of each train is 300, and the unladen weight of a complete train unit about 90 tons. The weight of train per passenger carried will therefore be 670 lb., and it is interesting to compare this with the average steam-hauled suburban train on British railways, which, including locomotive, weighs in the neighbourhood of 1,200 lb. per passenger.

The power units consist of two diesel engine generating sets in each train, one being located at each end; the engines are of the Company's six-cylinder H-type solid injection 4-stroke units, capable of developing 220 b.h.p. at 1,500 r.p.m. direct coupled to a main and auxiliary generator, the whole unit being flexibly mounted at three points as shown in Fig. 2. This mounting is a special and unique feature developed by the Company and is used on all their traction type diesel engines; it effectively relieves the engine of any stresses which might be set up due to flexing of the locomotive or railcar underframe. The pedestals of the three-point suspension are also insulated from the frame with rubber blocks which prevent vibration being transmitted to the underframe from the engine and *vice versa*.

In actual service these engines will only be called upon to develop 180 b.h.p. at 1,350 r.p.m.; thus a large margin of power is available if

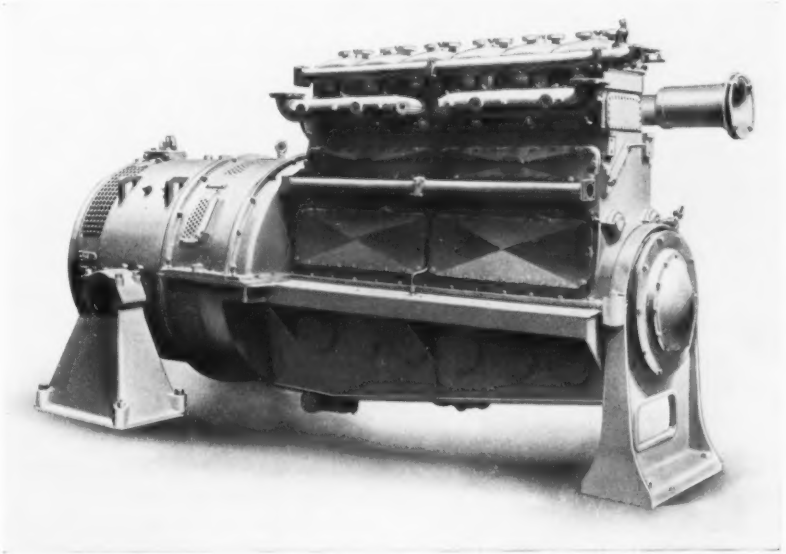


Fig. 2.—Showing Three-point Flexible Mounting of 220 b.h.p., 1,500 r.p.m. "English Electric" Diesel Engine Generating Set for Rail Cars.

required. The engines now under construction, whilst having many improvements embodied in them, remain essentially the same proved and successful units developed and first projected as early as 1928.

The drive is taken through four standard nose-suspended traction motors, two being mounted on the end-bogies of each train. The twin power units adopted have a number of advantages for this class of work. Firstly, should some fault develop in one power unit, it will always be possible for the train to reach its destination on the remaining unit. Secondly, by splitting up the equipment, the weight at either end of the train is reduced, compared with what it would be if all the power equipment were located at one end. On a suburban service requiring complete reversibility, this is an advantage, as the tendency to nose and to tail swing is reduced. An additional advantage is that the weight of the train is evenly distributed, enabling ample adhesion to be obtained on the driving wheels, despite the lightweight construction and without the use of sanding gear. Furthermore, in the layout of the trains it has been found possible to keep the centre of gravity of the power equipment well inside the end-bogie king-pins without encroaching unduly on the useful floor space, thus improving the riding qualities of the train.

The control system adopted, consisting of generators with a special characteristic, has been developed by the Company and used on numerous petrol and Diesel-electric traction drives. It combines the features of automatically limiting in a simple manner the load which can be thrown on to the engines with the absence of delicate relays and other apparatus, simplicity being of particular importance on a railway where expert advice is not readily available.

The driver's compartments will be arranged with built-in control desks on which are mounted the various power equipment, speed indicators and time recorders and brake gear indicators, with warning lights, etc., the actual operation of the trains being carried out entirely by two levers, one controlling the direction of travel and the other the speed of the engines and hence the power output. The interior of the driver's cabs will be entirely devoid of the usual untidy runs of cable and piping, all the equipment being located in an accessible position inside the control desk.

The most interesting departure from conventional practice concerns the coaches and underframes. Articulation is now well established both in this country and abroad, the most recent example being the Silver Jubilee trains of the L.N.E.R. Briefly, articulation saves train weight by eliminating, on a 4-coach unit, three bogies, and improves riding qualities by making the train operate as one unit instead of as a number of individual coaches.

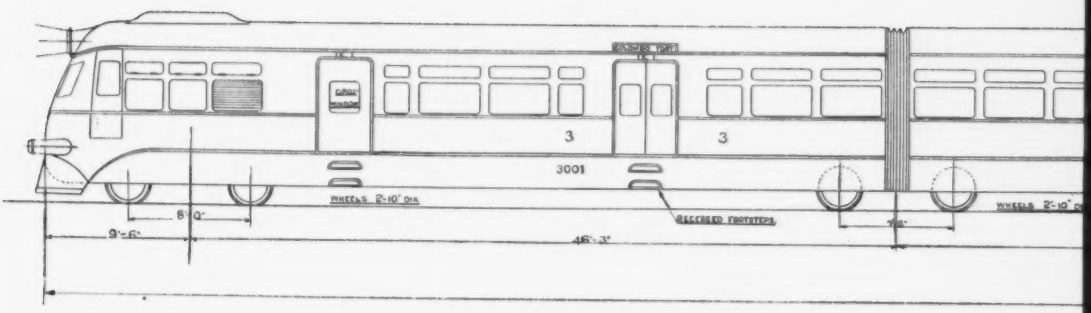
The underframes of the coaches are of plate girder construction and continuous fore and aft fitted with cantilever brackets carrying the body, which is integral with the underframe, the complete structure being all welded.

The bogies are of all-welded construction, fitted with swing bolsters and clasp-type brakes; the wheels are of the solid disc type to reduce weight.

The body pillars, cantrails, etc., are of special sections formed by rolling and extruding, scientifically designed to combine great strength with light weight.

All body panelling and framework is of copper bearing corrosion resisting steel and the panels and framing are welded throughout. In the development of this form of lightweight construction a very close study has been made of continental and American designs, and, in addition, the Company has been able to draw largely on its wide experience of all-welded bus and tram bodies.

Some comparative figures may be useful as illustrating the value of this form of construction. The average weight of a British railway passenger coach (8 ft. 6 in. wide) is equivalent to about 1,000 lbs. per foot run. The weight of the Ceylon coaches (9 ft. 10 in. wide) will be approximately 500 lbs. per foot run. It is not perhaps generally realised that railway engineers are as fully alive to the value of lightweight construction as are modern motor car manufacturers, but the railways must be of necessity extremely wary of new developments, and it is only during comparatively recent years that the technique of


3
3
3001
WHEELS 2'-10" DIA
ELECTRIC FIGHTERS
6'-0"
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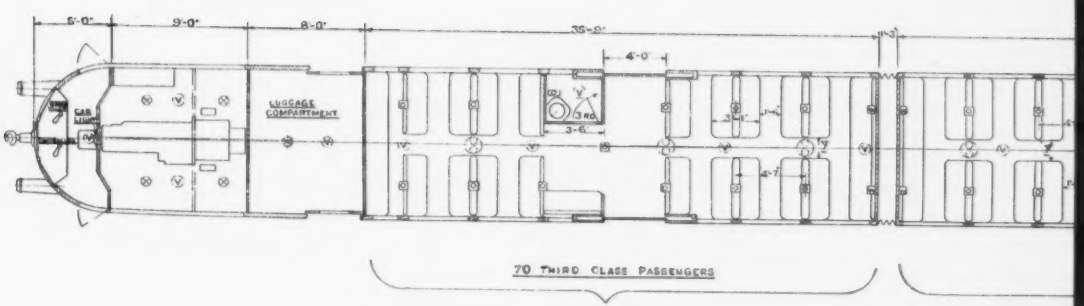
5'-0"
9'-0"
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35'-9"
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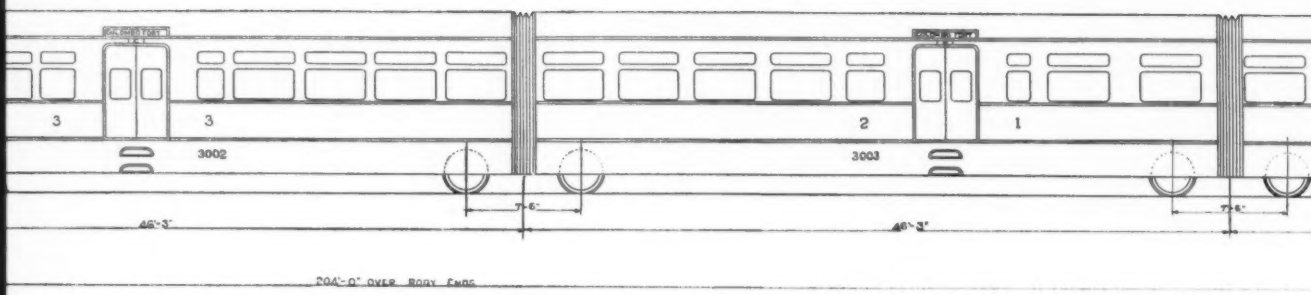
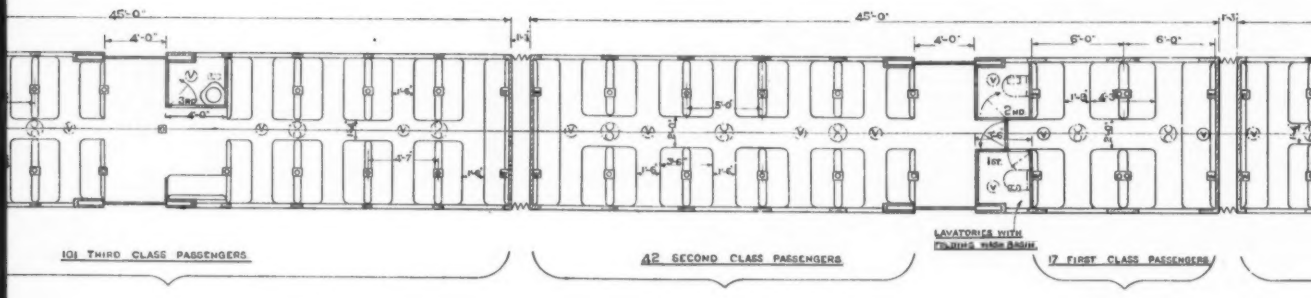
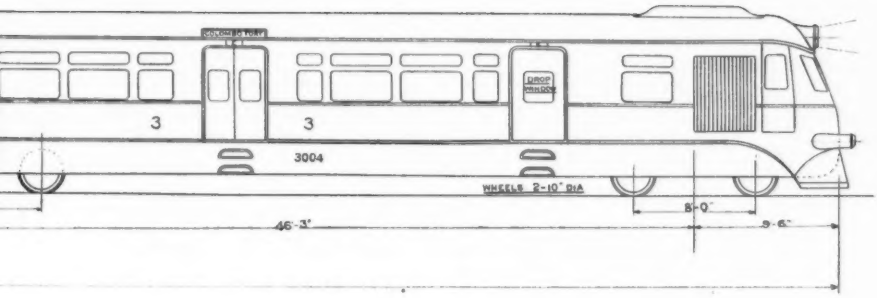
CAR LIGHT
LUGGAGE COMPARTMENT
3RD.
3'-6"
4'-7"
70 THIRD CLASS PASSENGERS

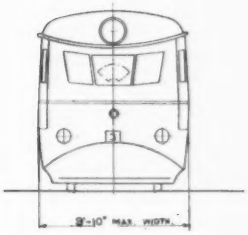




CEYLON GOVERNMENT RAILWAYS.

GENERAL ARRANGEMENT OF 4-COACH ARTICULATED DIESEL-ELECTRIC TRAIN.





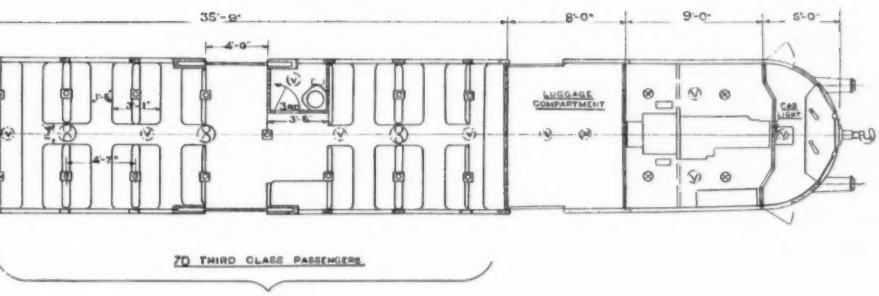


PLATE I.

[*The English Electric Journal.*

lightweight welded body work has developed sufficiently to warrant its use by the railways.

In the case of the Ceylon coaches, with the exception of the floors and a few internal fillets and mouldings, there will be no wood in the coaches. The interior fittings, lighting, seating, ventilation fans, etc., are all of a thoroughly modern and luxurious type.

The seats in the second and third class compartments are of tubular construction and the cushions of Dunlopillo, while those in the first class compartment are of lightweight alpax framework. It is interesting to note that these will be the first trains in Ceylon with ventilating fans and upholstered seats in the third class accommodation. The passenger compartments are fitted with balanced lift-up windows and louvres, easily operated by the passengers by means of leverlock catches. Toilet compartments are provided at each end. The vestibule entrance doors are of the double sliding type and central gangways are provided between the seats. All exposed interior metal fittings will be of oxidised brass, and have been specially designed to harmonise with the general scheme of decoration.

A number of twelfth scale models of the end-coach of one of the trains were made and painted in the Ceylon Government Railway colours, and from these a final model has been constructed combining, as far as possible, æsthetic and practical values. Finally, a full-size mock-up was constructed at Preston Works of one coach-end complete with driver's compartment, and from this mock-up the lines, positions of windows and driver's controls, etc., were determined before manufacture was commenced.

The automatic vacuum brakes and running gear generally follow standard railway practice and, so far as possible, embody the standards of the Ceylon Government Railways. One modification, however, which is of interest, is that roller bearing axle boxes are being employed.

In actual operation the trains will be limited to a maximum speed of 45 m.p.h., due to service regulations, but it is anticipated that the units will be capable of 55/60 m.p.h. fully loaded on level track. It may be found in service, due to the light axle loading and smooth drive, that speeds higher than 45 m.p.h. will be permissible. Provision has also been made to enable two complete trains to be run in multiple unit, controlled from one driving compartment, thus making an 8-coach train. Also, when required, it will be possible to take out one coach and run the remaining three coaches as a unit, giving increased performance and enabling the unit to be used for different classes of traffic and on routes which necessitate negotiating severe gradients.

It will be appreciated that considerable development work has been associated with the design of these trains and that in this article it has not been possible to go into the many interesting details. The unique position of the Company in designing and manufacturing the complete trains, including diesel engines, electrical equipment, mechanical parts and bodies, has made this development possible, and the Company's long experience in all forms of railway traction is an additional guarantee of satisfaction.

The Ceylon trains described are typical of the latest development of the traction department, but it should be mentioned that the Company also has under construction a number of railcars embodying the same principles and employing straight electric and Diesel-mechanical transmission.

Scientific Developments in Transformer Construction.

By R. M. CHARLEY, M.C., B.Sc., M.I.E.E., Mem.A.I.E.E.

NOTE.—In the September (Vol. VIII, No. 3) issue of this Journal the first section of this article described some of the latest developments in modern transformer design, and in the following section two recent examples of outstanding interest are described.

LARGE TRANSFORMERS AT FULHAM.

The very latest example of a Super Power Station is the one at which service was recently inaugurated at Fulham by the Fulham Metropolitan Borough Council, and it is an interesting fact that one of the most modern examples of large transformers are those recently supplied by the Company for the Central Electricity Board's Transforming Station at the Fulham Power Station.

The function of this Power Station is not only to supply the local load, but also to export power to the Grid. The Fulham 66 kV. busbar is coupled to the 132 kV. Grid at Willesden through these transformers, which are of 45 mV.A. capacity. The connections are star/star ; a delta-connected tertiary winding is provided, and its equivalent capacity is one-third of the normal rating of the transformer. The 132 kV. winding is arranged with graded insulation, the neutral being solidly grounded to the core, and the 66 kV. winding is fully insulated. On-load tap-changing gear is provided on the 132 kV. winding to allow for a voltage variation of plus and minus 10 per cent. in 14 steps, assuming the L.V. pressure of 66 kV. is maintained constant. Connections are made on both H.V. and L.V. sides through single-core oil-filled cable. A complete transformer erected on site is illustrated in the *Frontispiece*.

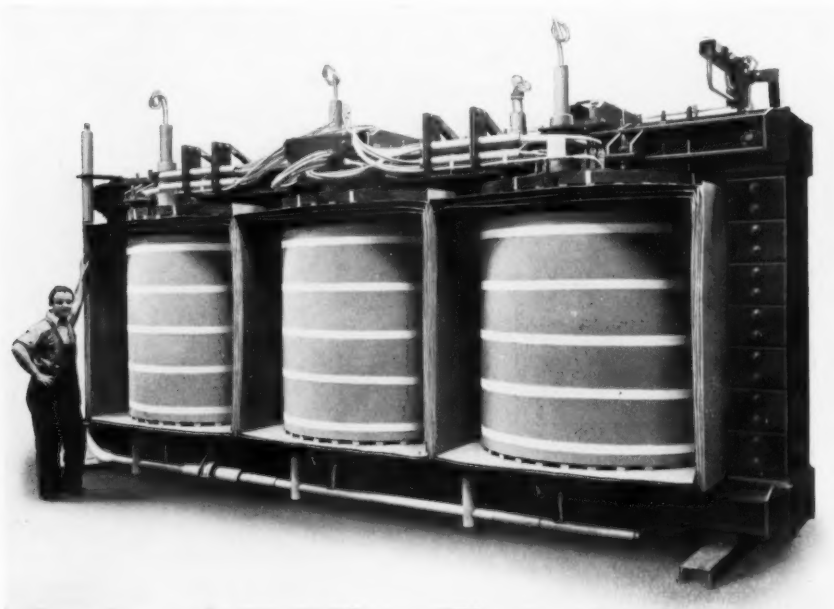


Fig. 8.—Complete core and windings of one of the 45 mV.A. transformers for the Fulham Transforming Station of the Central Electricity Board.

Fig. 9.—Transport by rail of a 45 mV.A. Transformer weighing 90 tons.

Five-Limb Core Construction.

Fig. 8 illustrates a complete core and windings. The core is of five-limb construction, the laminations of the limbs being interleaved with the yokes ; in both the main and auxiliary limbs the laminations are clamped with a single row of insulated bolts and steel clamping plates. On account of the large size of the main limbs, it is necessary to provide cooling ducts and these are arranged in the manner illustrated in Figs. 2 and 3 of the September (Vol. VIII, No. 3) issue of this Journal. The yokes are clamped by means of substantial welded steel frames, which are bolted to the yokes by five large diameter insulated bolts on the centre line of each limb. Each pair of frames is connected by cross saddles in line with the three main limbs, and on each side the top and bottom saddles are connected by high-tensile steel bolts, which pass down along the face of the limb inside the winding. This design ensures that lifting stresses, and those imposed on the main frames by forces produced in the windings during short-circuit conditions, have no effect on the insulated core bolts through the yokes and frames.

The main frames are suitably designed to provide adequate support for, and clamping of the windings, these supports being arranged to give the necessary strength without impeding the flow of oil to the windings and limbs.

A valuable feature of the five-limb core construction is that since the cross section of the yokes is approximately half of that which it would be with a three-limb core, the height over the top yoke is considerably reduced, which necessitates a much lower tank height, and, consequently, transport, particularly by rail, is greatly facilitated.

Transport of Large Transformers.

Fig. 9 illustrates the method of transport by rail of a 45 mV.A. transformer weighing 90 tons. The vehicle used is one of several that have been built by the various Railway Groups, the design having been determined in collaboration between the Railway Engineers and Electrical Manufacturers. The vehicle comprises four six-wheel bogie trucks, two at each end, and above each pair of trucks is mounted a platform pivoted at each end to the centre of the bogie truck, and the main frame of the vehicle is pivoted at each end to the centre of the two platforms. This vehicle is capable of transporting a load of 120 tons, and in the ordinary way can be employed for normal freight traffic.

Generally speaking, there is no facility for handling a large transformer by means of a crane after it leaves the manufacturer's works. The tank is so constructed that the whole weight, including core and windings and oil, can be supported when the tank is carried on the side frames of the railway vehicle by means of lugs welded to the top of the tank sides, as shown in Fig. 9. On arrival at its destination, the tank is jacked up until it is clear of the side members of the vehicle, and then one of these members is unbolted and removed, after which the transformer is moved away on rollers to its final position. It is interesting to note that wheels are not provided ; this practice has been determined by experience which has shown that in the handling of transformers of even the largest sizes, it is preferable to use long bar or tubular rollers under a suitably designed base, rather than to provide wheels as an integral part of the transformer.

Special Arrangement of Windings.

The H.V. and L.V. windings are arranged in a double concentric form. The tertiary winding is wound in a disc spiral manner on a bakelised paper cylinder and is located next to the core limb. The H.V. regulating winding is similarly wound and is located outside the tertiary winding. This arrangement of tappings produces the most consistent values of impedance on the various tappings and results in the minimum of dis-symmetry on any tapping position, thus restricting the vertical component of the short-circuit forces exerted on the top and bottom frames to a minimum. The first section of the H.V. winding is located outside the regulating winding and one end of it is solidly grounded to the core. Outside this section is the L.V., or 66 kV., winding and, finally, there is the outer section of the H.V. winding, the upper end of which is connected to the line terminal. The H.V. and L.V. windings are formed of double-section coils wound with a paper-insulated conductor. The tappings from the regulating-winding are brought up to the top of the winding by means of flat copper strip insulated in tubes of bakelised paper and are then connected to flexible paper-insulated cable for connection to the multiple bushings of the On-load Tap-changing equipment.

Special Tank and Cable Box Construction.

The tank is entirely welded and, in addition to its construction being suitable for transport conditions as described above, it is also specially reinforced in order to minimise the emanation of noise. To produce this result to the best possible degree, it is necessary to locate a large number of stiffening ribs on the tank sides, thus sub-dividing the plates into many comparatively small panels. This feature may be seen in the *Frontispiece*.

As previously stated, connections are made to the transformer by means of single-core oil-filled cable. The cable is sealed with a special sealing-end supplied by the cable manufacturer, and this end is supported in an oil-filled chamber mounted on the cover of the transformer tank. This chamber is open to the main tank and connection is made from the transformer winding to the cable sealing-end by means of a flexible paper-insulated cable, and where connection is made to the sealing-end there is a suitable corona shield. This arrangement gives a very simple means of making the cable connection to the transformer winding, and should it be necessary to remove a cable sealing-end from the chamber on the transformer, it is necessary to remove only a comparatively small volume of oil.

O.F.B. Coolers.

Cooling is provided by two separate coolers, each comprising a number of radiators built up of elliptical tube welded into headers at top and bottom, these headers being connected to main oil trunks through simple valves, which make it possible for any single radiator to be detached, if necessary, with the minimum of disturbance to the oil or to the structure. The main oil connections from the tank to the coolers are of large diameter, and are coupled to the main trunks through gunmetal flanged gate-valves, by means of which the coolers can be entirely separated from the main tank. There is also a similar valve at the oil inlet at the bottom of the main tank. Coupled to this valve and in the main oil circuit

is a motor-driven impellor-type pump, which, when running, accelerates the flow of oil through the cooler and, when stationary, offers negligible impedance to the flow of oil. Underneath the radiators of each cooler is mounted a motor-driven fan, which supplies air to a main air diffuser coupled to individual diffusers, which distribute the air to the tubes at the bottom and also halfway up the radiators.

The radiating surface of the coolers is sufficient to enable the transformer to carry 50 per cent. of its normal output under natural cooling conditions, i.e., with the fan and oil pump not running. The motors of the fans and oil pumps are automatically controlled by thermostats located in the hot oil, one being arranged to start the motors at a certain predetermined oil temperature, the other being used to stop them when the temperature of the oil has fallen to another predetermined value.

Buchholz Protective Device.

Mounted above one cooler is an oil expansion vessel of adequate proportions to allow for the maximum expansion of oil. Connection to this expansion vessel is made through pipes coming from the highest point of the main oil pipes to the coolers. Provision is made in the expansion vessel pipe for mounting a Buchholz protective device, a brief description of which may be of interest. Fig. 10 shows a device suitable for the transformers under discussion. The device functions on the fact that any fault occurring in an oil-immersed transformer gives rise to the evolution of gas, which naturally rises through the oil in an attempt to escape, and in passing up the expansion-vessel pipe it reaches the device. In the oil chamber of the device there are mounted two floats, one in the upper oil space and the other at the bottom directly in line with the expansion-vessel pipe. Each float is provided with a mercury-break switch, which is used in conjunction with alarm or tripping circuits ; the usual practice is to connect the upper float to give an alarm and the lower float to trip the circuit breakers. As gas collects in the upper part of the chamber, the float gradually falls until the mercury switch makes circuit and a warning is given. In the side of the device is a gauge, by observation of which some idea may be obtained of the rapidity with which gas is developing, thus giving some indication of the severity of the fault. In the event of a fault being of such magnitude that the gas has not time to collect in the device, a pressure is produced in the oil which causes a surge of oil along the expansion-vessel pipe to the device, and this surge, impinging on the lower float, causes its mercury switch to operate.

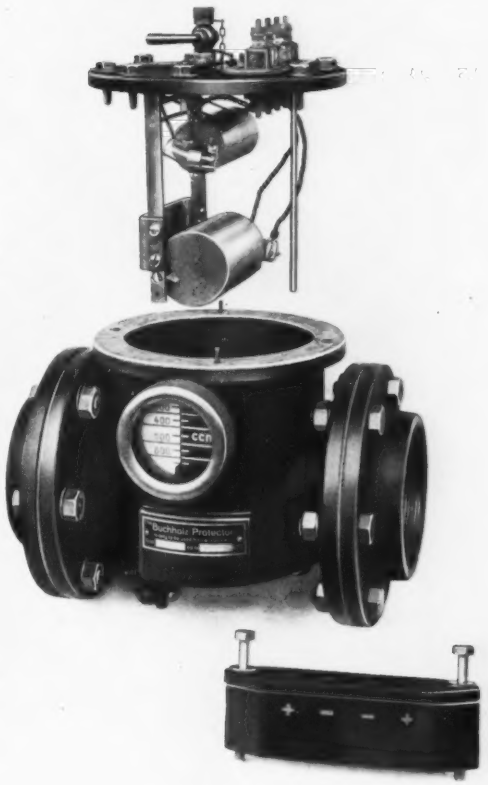


Fig. 10.—Buchholz Protective Device.

The great value of the Buchholz protective scheme is that it gives protection against certain faults, which would pass unnoticed by the usual electrical forms of protection, e.g., gradual breakdown of insulation between turns, open sparking through the oil, and overheating of core, due perhaps to failure of core-bolt insulation. A

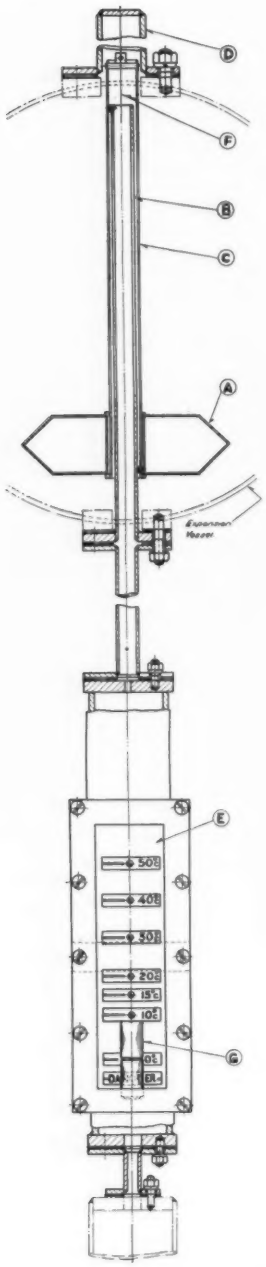


Fig. 11.—Arrangement of Float-Type Oil Gauge.

further useful application of the device is for the protection of oil-immersed apparatus, such as earthing transformers, earthing resistances and reactors, in connection with which it is almost impossible to apply the usual forms of electrical protection.

Patented Float Type Oil Gauge (Pat. No. 450419).

The oil gauge which is seen in the *Frontispiece* immediately below the expansion vessel on the right-hand side of the cooler is of a unique and interesting type ; it is shown in section in Fig. 11. It comprises an annular float (A), which floats on top of the oil concentrically with a vertical pipe (B), which passes down through the bottom of the expansion vessel. To the top of the float is fixed a long tubular stirrup (C), which surrounds the vertical tube and extends above it, even when the float is in the lowest position, whilst in the highest position it is encased in a protecting tube (D) bolted to the top of the expansion vessel. The lower end of the central pipe is extended to a chamber (E) located at eye-level. From the top of the stirrup is suspended a steel wire (F), to the end of which is hung a weight and level indicator (G), which is visible through a glass window in the chamber. An interesting feature of this oil level gauge is that it is calibrated and marked in degrees C., for the oil level is proportional to the oil temperature. The gauge chamber and the piping is airtight, and to the lower end the Silica-Gel breather is connected.

In the *Frontispiece* will be seen a large diameter pipe projecting from the left-hand end of the tank cover and extending up to a level above the expansion vessel with the end turned through 180 deg. to face the ground. This pipe contains the explosion diaphragm, and it is located in such a manner that under any fault condition it has no influence on the satisfactory operation of the Buchholz device.

The On-load Tap-changing gear is of the Company's well-known type, which has been employed on about two and a half million kVA. of transformers now in service, ranging through every size up to 45 mV.A., and for all service voltages up to 132 kV.

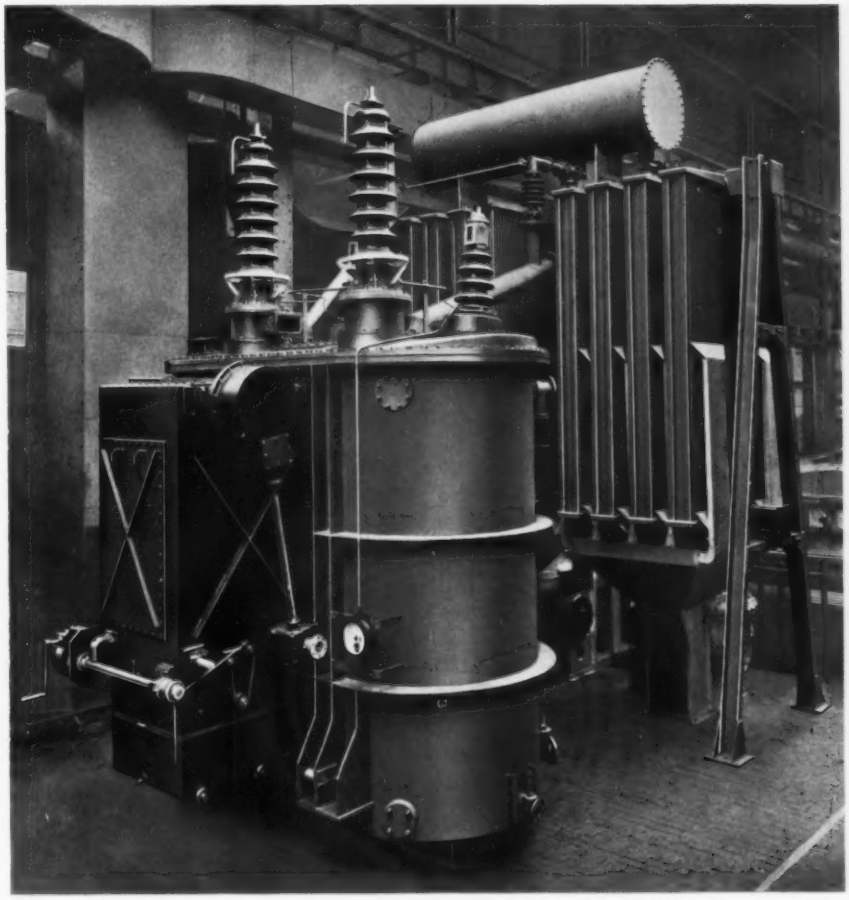


Fig. 12.—Single-phase Transformer Unit complete with air-blast cooled oil-cooler. Three such units are connected together to form a Three-phase Bank of 55 mV.A. capacity.

55 mV.A. Banks of Transformers for South Africa.

This section of this article refers to some interesting transformers supplied to the Victoria Falls & Transvaal Power Company, Ltd., for use in stepdown substations supplied from the new Klip Power Station. The transformers are single-phase units, three units being connected together to form a three-phase bank of 55 mV.A. capacity, the voltage ratio being 76/42 kV., the windings being connected star/delta. On the H.V., or 76 kV. side, On-load Tap-changing equipment is provided to allow for a voltage variation on the H.V. side between 68 kV. and 84 kV. in 16 steps.

In the case of two substations separate water-cooled oil-coolers are provided, the oil being pumped through the transformer and cooler by a motor-driven centrifugal-type pump. At two other substations separate air-blast cooled oil-coolers are provided, the circulation of oil through the radiators being natural, there being no oil pump. Otherwise this cooler follows the same general construction as that described on page 106. Fig. 12 illustrates one single-phase unit complete with air-blast cooled oil-cooler.

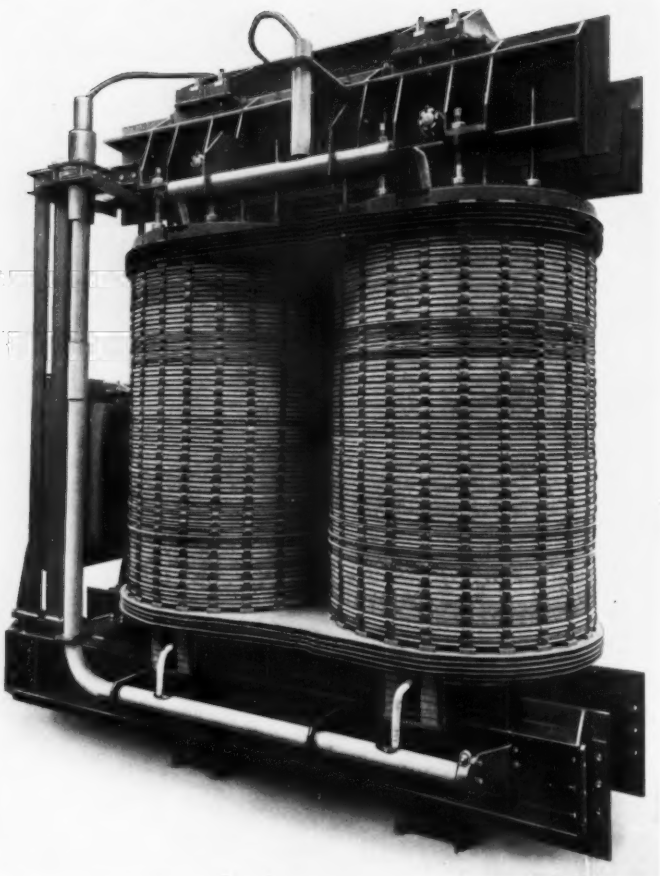


Fig. 13.—Core and Winding of Transformer illustrated in Fig. 12, voltage ratio 76/42 kV.

All units are made identical and with suitable pipe connections and valves, so that any unit may be used in conjunction with either type of oil-cooler.

Single-phase Core and Windings.

The transformers are of the single-phase core-type with two limbs as illustrated in Fig. 13. The general construction of the core and frames is similar to that described on page 105.

The L.V. winding is formed as a disc spiral on a bakelised paper cylinder, vertical fullerboard spacers forming an oil duct between the cylinder and the winding. Fullerboard sectors dovetailed on to the vertical spacers form oil ducts between the various discs in the winding. The conductor comprises two paper-insulated wires in parallel, and these are transposed at every section. Fig. 14 shows the winding of an L.V. coil. The transposition of the wires is clearly shown, and the two places where the turns are widely spaced correspond to the positions in the H.V. winding where the tappings are located. This feature is another example of the special construction described on pages 85 to 87 of the September (Vol. VIII, No. 3) issue of this Journal. The other wide space in the winding is opposite the centre of the H.V. column of coils where the reinforced

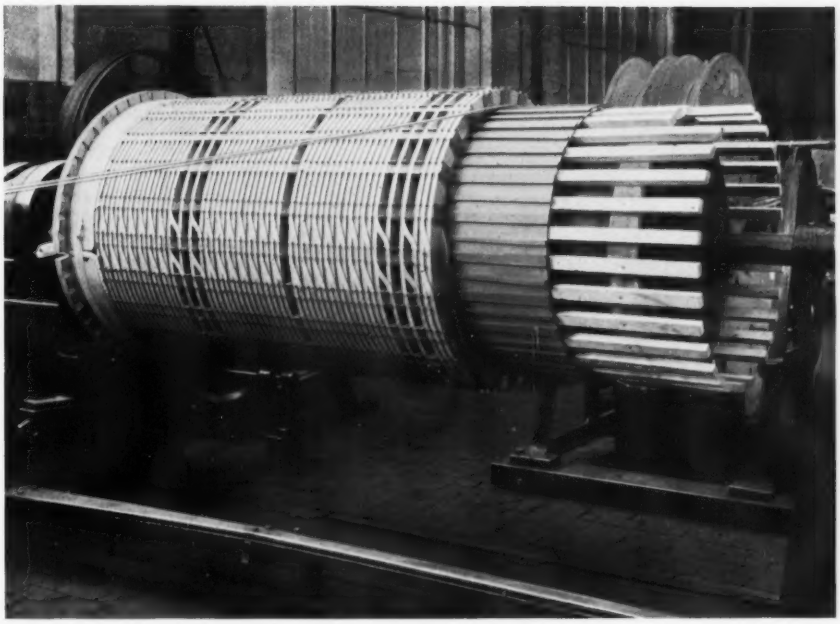


Fig. 14.—Showing the winding of one of the L.V. Coils.

line turns are located, the upper and lower halves of each column of H.V. coils being connected in parallel. The main value of this scheme is the reduction of the unbalanced mechanical forces under short-circuit conditions to a minimum value, and the consistency of the impedance throughout the tapping range. In the case of the transformers now being described, the tapping range is 24 per cent. and the maximum variation of impedance is only 6 per cent.

The H.V. winding comprises a number of double-section disc coils, the conductor comprising two paper-insulated rectangular wires. The two sections of the coil are separated by fullerboard sectors and are held together with a wrapping of fullerboard insulation, embracing each sector and both coil sections. In the assembly of the column of coils this wrapping forms the spacers between coils. Fig. 15 shows two double-section coils. The tappings are located at the middle of the upper and lower halves of each column of coils and are brought out to the On-load Tap-changing equipment by means of paper-insulated flexible cable supported in substantial tubes of bakelised paper.

The H.V. bushings are of the condenser type protected with single-piece porcelain shields, making them suitable for outdoor service, and the wet flashover value is 250 kV. In one H.V. bushing is a potential indicating tapping. The L.V. bushings are of single-piece oil-filled porcelain.

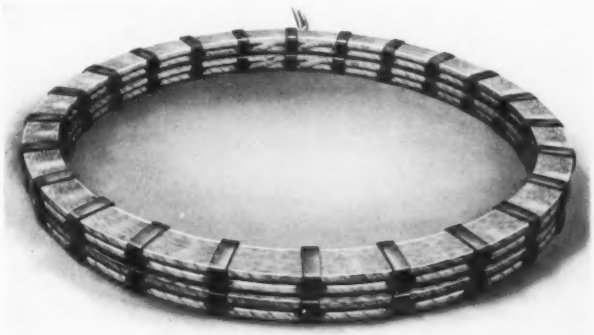


Fig. 15.—Two Double-Section Coils of the H.V. Winding.

Unique On-load Tap-changing Equipment.

The On-load Tap-changing gear is interesting from the fact that it has to deal with a load current of 470 amperes and is fully insulated for a test pressure of 180 kV. Electrically, the scheme follows the Company's standard practice. The selector switch is mounted in a chamber which is bolted to the tank side, and the various connections from the fixed contacts of the switch are taken by means of paper-insulated flexible cable through a large opening in the tank side to the tappings on the main winding and to the mid-point auto-transformer which is mounted on an extension of the lower frames of the main transformer. Access to this chamber is gained through a cover mounted on the front of it, but it is rarely necessary for this part of the equipment to be examined.

Below the selector switch chamber is mounted the pair of divertor switches, connection to which is made by means of condenser bushings mounted in the bottom of the selector switch chamber, these bushings also forming a support for the fixed contacts of the switch. The moving portion of each divertor switch is operated by a cam mechanism, the two switches operating alternately. This portion of the equipment is contained in a separate oil tank which is supported from the bottom of the selector switch chamber, and, by means of rope lowering gear, can be opened up for inspection in a very short time.

Fig. 16 shows one single-phase equipment with front cover removed and tank lowered, and Fig. 17 shows a pair of divertor switches in detail.

The operation of the selector switch is effected by a Geneva motion, which is mechanically coupled with the cam mechanism operating the divertor switches, so that the correct sequence of operations is assured. The operating mechanism of three units forming one bank is coupled together by horizontal shafting and to the motor operating gear mounted on the floor between two of the units. Fig. 18 shows the motor operating gear cabinet.

Remote electrical control of the On-load Tap-changing equipment is provided, and indication of the tapping position is given at the remote point. By a simple addition, it would be possible to convert these equipments to automatic control.

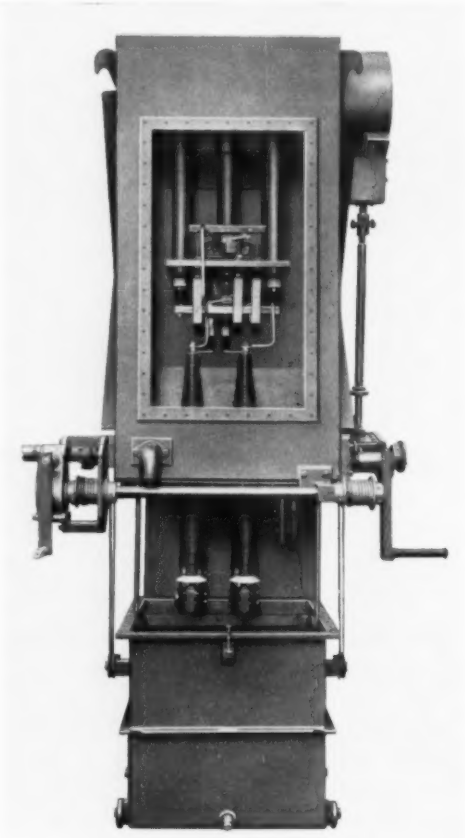


Fig. 16.—Single-phase On-load Tap-changing Equipment with front cover removed and tank lowered.

These transformers were dried out under the usual vacuum process at the Works and impregnated with hot transformer oil, which was later drawn off in such a way that air, coming in to replace the oil, passed through a drying equipment, and after all the oil had been withdrawn the tank was sealed. In this condition the complete core and windings, in its tank, but without bushings, expansion vessel and On-load Tap-changing gear, was transported to site and no drying out on site was necessary. The weight of each unit arranged in this manner for transport was 28 tons.

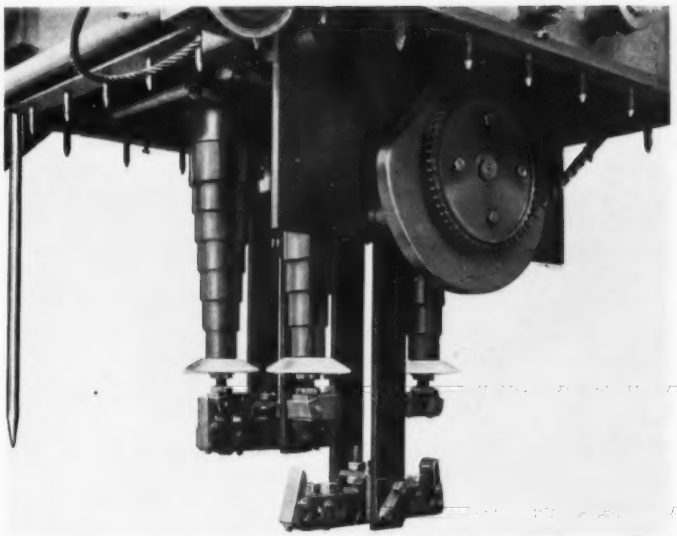


Fig. 17.—Pair of Divertor Switches for On-load Tap-changing Equipment.

Fig. 18.—Motor-operating Gear Cabinet for On-load Tap-changing Equipment.

Determination of Turbine Disc Stresses.

By S. J. E. MOYES, B.Sc., Steam Turbine Dept.

(*Reprinted from "Engineering," 31st July, 1936.*)

The following method of determining stresses in turbine discs is an extension of the one described in ENGINEERING, October 5th, 1923, by G. Arrowsmith, which consists of considering comparatively small sections of a disc, step by step. The method described in this article is based primarily on the original "step" method, but enables the working to be cut down to the consideration of profile change points, besides only having to make one complete calculation for the disc, as against two and the possibility of three in the original "step" method.

The original "step" method consists of treating each section as a disc having a form corresponding to

$$y = \frac{c}{x^a}$$

where

y = disc thickness at any radius x,
c = a constant for the disc,
a = index of the hyperbolic profile.

By means of the fundamental equations for the radial and tangential stresses in a disc having the form $y = \frac{c}{x^a}$, Arrowsmith derived constants enabling a solution for the tangential stress at the hub to be found, and hence the radial and tangential stresses in any part of the disc.

Thus, the radial and tangential stresses, referring to Fig. 1, are :—

Radial stress σ_{r1} at x_1

$$= A\,\sigma_{r0} + B\,\sigma_{t0} - C\,K\,x_0^2$$

Tangential stress σt_1 at x_1

$$= E\,\sigma_{r0} + F\,\sigma_{t0} - G\,K\,x_0^2$$

where A, B, C, E, F, and G are constants derived by Arrowsmith from the fundamental equations, depending upon

$$\frac{x_1}{x_0} \text{ and } \left(\frac{y_0}{y_1} = \rho\right)$$

and assuming that between x_1 and x_0, $y_1\,x_1^a = y_0\,x_0^a$, i.e., a hyperbolic profile between x_1 and x_0.

σ_{r0} = Radial stress at x_0
σ_{t0} = Tangential stress at x_0.

$$K = \frac{w\omega^2}{g},$$

where w = density of disc material,
ω = angular velocity of the disc,
g = acceleration due to gravity.

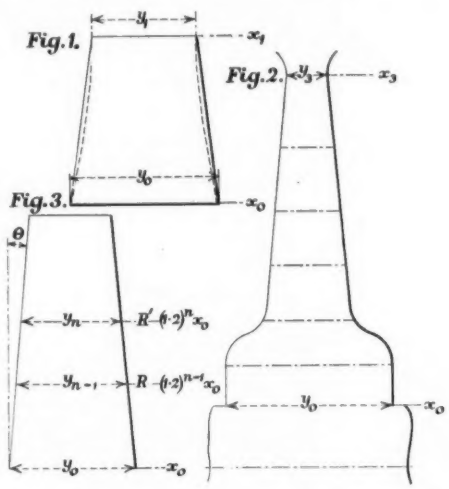


Fig. 4. TAPER DISC.

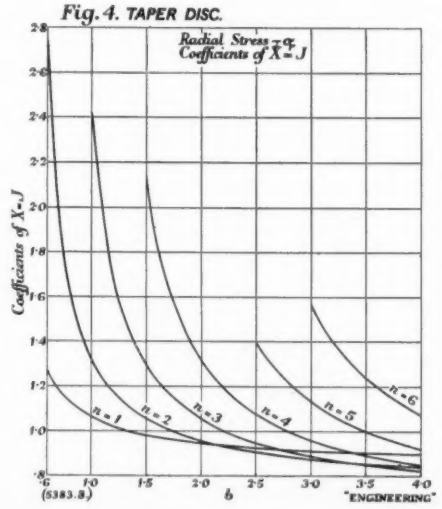


Fig. 5. TAPER DISC.

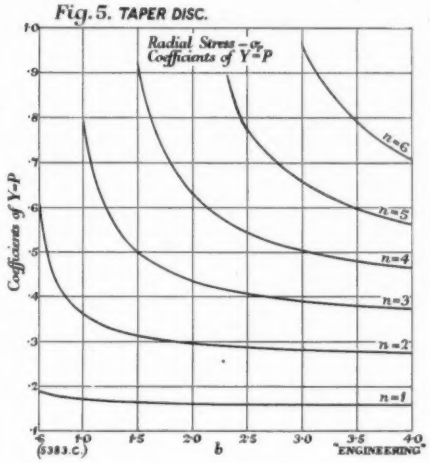


Fig. 7. TAPER DISC.

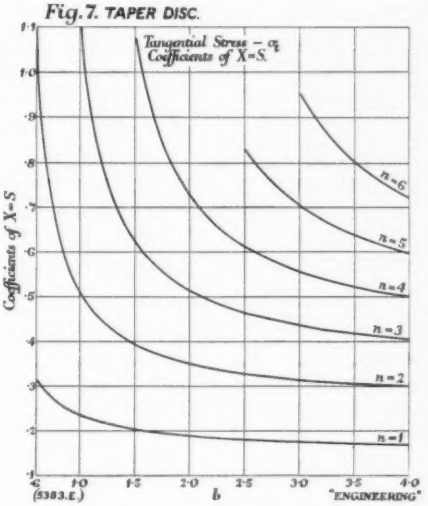


Fig. 6. TAPER DISC.

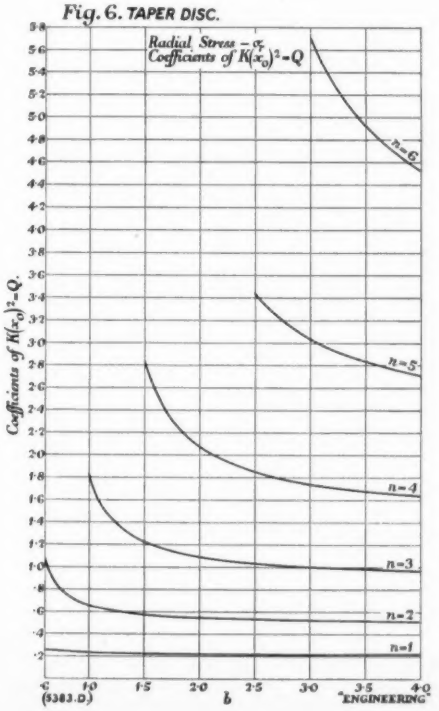
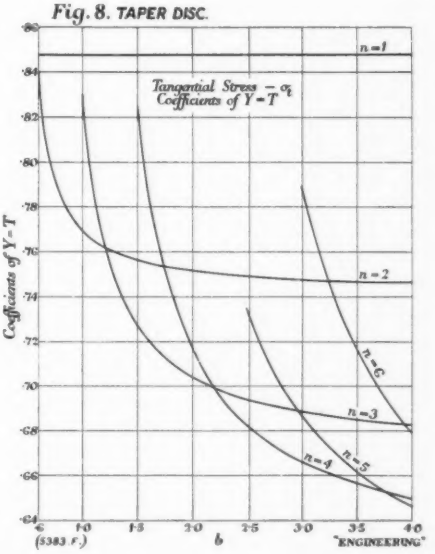


Fig. 8. TAPER DISC.



Thus, the method used in an actual calculation for a disc is as follows, referring to Fig. 2 :—5 per cent., 10 per cent., or 20 per cent. radial increases on the previous radius are stepped up from x_0 until x_3 is reached and the disc widths measured at each radius.

Assuming at hub, radius x_0, the radial stress σ_r is zero, and a likely value for the tangential stress σ_{t0}, the radial and tangential stresses at x_3, the disc neck can be found, since for any section the constants A, B, C, E, F and G can be found, as given by Arrowsmith.

The external load carried by the disc for the assumed hub conditions is given by the equation

External load = L

$$L = 2\pi A_r \left[\sigma_{t3} - K x_4^2 + \sigma_{r3}\left(\frac{y_3 x_3}{A_r} - \nu\right)\right]$$

where

A_r = cross sectional area of the disc rim,
σ_{t3} = tangential stress at neck rad. x_3,
σ_{r3} = radial stress at neck rad. x_3,
x_4 = rad. of C of G of the disc rim,
ν = Poisson's ratio.

If the load calculated agrees with the actual external load on the disc, the assumed hub conditions are correct, but if no agreement occurs, a new tangential stress is assumed and a fresh calculation made, this procedure being continued until interpolation can be made between two sufficiently near values of the calculated external load, a method which in most cases entails three sets of calculations, with a possibility of more, should the hub tangential stress, or any stress in the disc, prove too high.

The only inherent error in the method is the fact that between any two radii, a hyperbolic profile is assumed, instead of the actual disc profile.

The following method is based entirely on Arrowsmith's step method and uses the constants A, B, C, E, F and G, as deduced by Arrowsmith for various values of $\frac{y_0}{y_1}$ and a constant value of $\frac{x_1}{x_0} = 1{\cdot}2$, i.e., all radial increases of the previous radius are 20 per cent.

First consider a straight taper disc as in Fig. 3 ; and let any radius $R^1 = (1{\cdot}2)^n x_0$.

Hence in accordance with the 20 per cent. radial increase, the previous radius $R = (1{\cdot}2)^{n-1} x_0$. Let y_n and y_{n-1} be the disc widths at these radii, and Tan θ = Slope of taper.

Thus for the radius R^1 under consideration :—

$$\rho = \frac{y_{n-1}}{y_n} = \frac{y_0 - 2\tan\theta x_0\{(1{\cdot}2)^{n-1} - 1\}}{y_0 - 2\tan\theta x_0\{(1{\cdot}2)^n - 1\}}$$

Dividing numerator and denominator by $2\tan\theta x_0$.

$$\rho = \frac{\dfrac{y_0}{2\tan\theta x_0} - \{(1{\cdot}2)^{n-1} - 1\}}{\dfrac{y_0}{2\tan\theta x_0} - \{(1{\cdot}2)^n - 1\}}$$

Let

$$b = \frac{y_0}{2\tan\theta x_0}$$

$$\therefore \quad \rho = \frac{b + 1 - (1{\cdot}2)^{n-1}}{b + 1 - (1{\cdot}2)^n}$$

Thus, for any given value of b, the values of ρ for $n = 1, 2, 3, 4 \ldots$ can be deduced, and consequently for each radius corresponding to $n = 1, 2, 3, 4 \ldots$ For example :—

If at radius R^1, $n = 3$,

$$\rho \text{ for rad. } R^1 = \frac{b + 1 - (1{\cdot}2)^2}{b + 1 - (1{\cdot}2)^3}$$

Hence the values of A, B, C, E, F and G for the various radii can be found.

If at x_0 Radial stress = X
Tangential stress = Y
then at the 1st step, $n = 1$

$$\text{Radius } x = 1{\cdot}2\, x_0 \quad \rho = \frac{b}{b - 0{\cdot}2}$$

A, B, C, E, F, G can be found from Arrowsmith's figures.

Thus at radius x $= 1{\cdot}2\, x_0$
Radial stress σ_r $= A\,X + B\,Y - C\,K\,(x_0)^2$
Tangential stress σ_t $= E\,X + F\,Y - G\,K\,(x_0)^2$
For the 2nd step $n = 2$

$$\text{Radius } x = (1{\cdot}2)^2 x_0 \quad \rho = \frac{b - 0{\cdot}2}{b + 1 - (1{\cdot}2)^2}$$

Hence, values of A, B, C, E, F and G can be found, and the radial and tangential stresses at radius $(1{\cdot}2)^2 x_0$ be found in precisely the same manner as before by using the radial and tangential stresses at the previous radius $x = 1{\cdot}2\, x_0$.

For example, if the values of A, B, C, E, F and G for radius $x = (1{\cdot}2)^2 x_0$ are A_1, B_1, C_1, E_1, F_1, G_1, respectively.

Then, for $n = 2$, i.e., at radius $(1{\cdot}2)^2\, x_0$

Radial stress σ_r

$$= (A_1 A + B_1 E)\, X + (A_1 B + B_1 F)\, Y - \{A_1 C + B_1 G + C_1 (1{\cdot}2)^2\} K (x_0)^2$$

Tangential stress σ_t

$$= (E_1 A + F_1 E)\, X + (E_1 B + F_1 F)\, Y - \{E_1 C + F_1 G + G_1 (1{\cdot}2)^2\}\, K (x_0)^2$$

It will thus be seen that for any radius $x = (1{\cdot}2)^n x_0$ the expressions take the general form

Radial stress $\sigma_r = J X + P Y - Q K x_0^2$.

Tangential stress $\sigma_t = S X + T Y - V K x_0^2$

the values of J, P, Q, S, T and V depending upon the value of n which must be integral and the value of b, denoting the shape of the disc.

Curves, then, can be plotted of values of J, P, Q, S, T and V for values of n and b, and these are given in Figs. 4, 5, 6, 7, 8, 9.

The calculations become very much simplified for a parallel-sided disc, and the fundamental equations can be used instead of any approximate methods, although Arrowsmith's step method becomes absolutely correct for a parallel-sided disc.

As the parallel-sided portions of a turbine disc occur always at the hub, the conditions at the hub can be stated, viz. :—

Radial stress is zero.
Tangential stress is f (unknown).

The fundamental equations are given in most text books dealing with the subject.

Radial stress σ_r at radius x

$$= A' + \frac{B'}{x^2} - \frac{(3 + \nu)\, w\, \omega^2}{8\, g}\, x^2$$

Tangential stress σ_t at radius x

$$= A' - \frac{B'}{x^2} - \frac{(1 + 3\nu)\, w\, \omega^2}{8\, g}\, x^2$$

where A′ and B′ are constants derived from hub conditions,

ν = Poisson's ratio,
w = Density of disc material,
ω = Angular velocity of disc.

Thus, if the hub radius $= x_0$

$$A' = \frac{f}{2} + \frac{1 + \nu}{4\, g}\, w\, \omega^2\, x_0^2$$

$$B' = \frac{1 - \nu}{8\, g}\, w\, \omega^2\, x_0^4 - \frac{f\, x_0^2}{2}$$

Thus, at any radius

$$x = \beta\, x_0$$

Fig. 9. TAPER DISC.

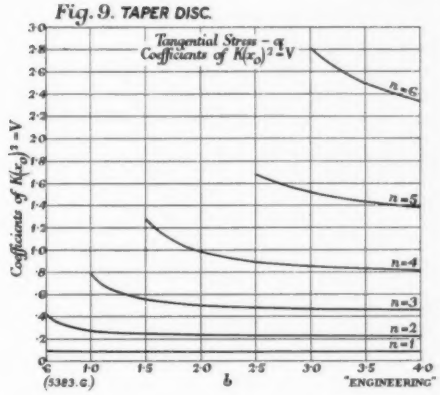


Fig. 10. PARALLEL-SIDED DISC.

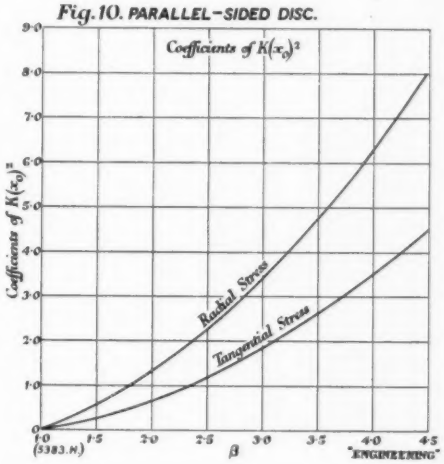
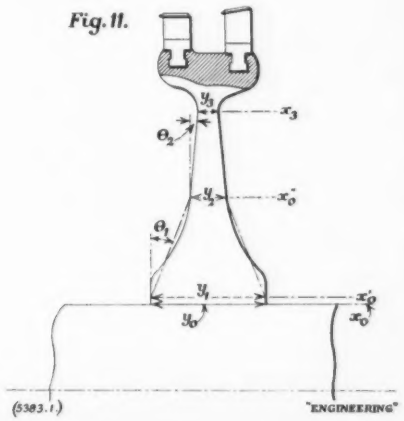


Fig. 11.



the equations take the following form :—

Radial stress σ_r

$$= \frac{f}{2}\left(1 - \frac{1}{\beta^2}\right) + w\frac{\omega^2 x_0^2}{8g}\left\{2 + 2\nu + \frac{1-}{\beta^2} - (3+\nu)\beta^2\right\}$$

Tangential stress σ_t

$$= \frac{f}{2}\left(1 + \frac{1}{\beta^2}\right) + w\frac{\omega^2 x_0^2}{8g}\left\{2 + 2\nu - \frac{1-\nu}{\beta^2} - (1+3\nu)\beta^2\right\}$$

Although a curve could be plotted for the coefficients of f, it is advisable to calculate these, as the curves are very steep for small values of β above unity and any error which might easily arise in the reading of such curves would be multiplied in the succeeding calculations. A curve for the coefficients of $K(x_0)^2$ against β is useful and has not the same limitations as the curve for coefficients of f;

$$\left(K = \frac{w\omega^2}{g}\right).$$

As shown in Fig. 10, for a reasonable range of β it is not steep, and any error, although multiplied by succeeding calculations, is minimised by the addition of larger quantities calculated from other curves.

The procedure for calculating stresses in an actual case is made clear in the example below :—

Disc for Curtis wheel, Fig. 11.

Speed 6,000 r.p.m. Nominal mean blade diameter = 22·0.

All dimensions are in inches.

Neck radius x_3	= 8·48	Width y_3	= 0·625
Radius x''_0	= 5·89	Width y_2	= 1·080
Radius x'_0	= 2·84	Width y_1	= 3·5
Hub radius x_0	= 2·625	Width y_0	= 3·5

θ_2 = Slope of upper taper.
θ_1 = Slope of lower taper.

Disc is of steel.

$$\text{Constant } K = \frac{w\omega^2}{g} = 289{\cdot}6 \text{ lb./in.}^4.$$

The neck radius x_3 is determined and is divided by an integral power of 1·2 to give a radius as near as possible to the commencement of the upper taper from the curved portion.

Thus :

$$\text{radius } x''_0 = \frac{8{\cdot}48}{(1{\cdot}2)^2} = 5{\cdot}89.$$

Radius x''_0 is then divided by an integral power of 1·2 such that the radius x'_0 arrived at is as near as possible to the join of the parallel-sided and curved portions of the disc and also that a straight line (shown dotted) joining the widths y_2 and y_1 has the curved portion distributed evenly around it. The meaning of this will be explained later.

Thus :

$$\text{radius } x'_0 = \frac{5{\cdot}89}{(1{\cdot}2)^4} = 2{\cdot}84$$

$$\text{Also } \frac{x'_0}{x_0} = \frac{2{\cdot}84}{2{\cdot}625} = 1{\cdot}081 = \beta.$$

Parallel-sided portion—x_0 to x'_0 :

$\beta = 1{\cdot}081$. $K(x_0)^2 = 6{\cdot}89$ K.

At hub radius x_0

Radial stress is zero,

Tangential stress is f.

At radius x'_0 :

Radial stress σ_{r1}

$$= \frac{f}{2}\left(1 - \frac{1}{\beta^2}\right) - 0{\cdot}09 \text{ K } x_0^2$$

$$= 0{\cdot}0722\,f - 0{\cdot}6201 \text{ K} = X_1.$$

Tangential stress σ_{t1}

$$= \frac{f}{2}\left(1 + \frac{1}{\beta^2}\right) - 0{\cdot}025 \text{ K } x_0^2.$$

$$= 0{\cdot}9278\,f - 0{\cdot}1722 \text{ K} = Y_1.$$

Curved portion—x'_0 to x''_0.—This portion of the disc is treated as a straight taper between radii x'_0 and x''_0, hence the drawing of a mean line through the curve, referred to previously.

This approximation can only be tested by actual calculation and the author has investigated a number of cases by this method and the original "step" method, the final results differing by less than 2 per cent., a margin which in the author's opinion is well within the inherent error in both methods of treating each step as having a hyperbolic profile. This being so, b can be calculated for the curved portion as for a straight taper.

$$b = \frac{y_1}{2\tan\theta_1 x'_0} = \frac{3{\cdot}05 \times 3{\cdot}5}{2{\cdot}42 \times 2{\cdot}84} = 1{\cdot}554.$$

$n = 4$. $K(x'_0)^2 = 8{\cdot}06$ K.

At radius x''_0 :

Radial stress = σ_{r2} :—

		f	K
Fig. 4.	Coeff. of X_1=(J)=	0·1411	−1·2115
,, 5.	,, Y_1=(P)=	0·8042	−0·1494
,, 6.	,, $K(x'_0)^2$=Q=	2·65	− 21·35
		0·9453	−22·711

$= X'_2$.

Tangential stress $= \sigma_{t2}$:—		f	K
Fig. 7. Coeff. of	$X_1 = S = 1{\cdot}005$	$0{\cdot}0726$	$-0{\cdot}6228$
,, 8. ,,	$Y_1 = T = 0{\cdot}8027$	$0{\cdot}7450$	$-0{\cdot}1383$
,, 9. ,,	$K\,(x'_0)^2 = V = 1{\cdot}235$		$-9{\cdot}952$
		$0{\cdot}8176$	$-10{\cdot}713$

$= Y_2$.

Upper taper — x''_0 to x_3 :

$$b = \frac{y_2}{2 \tan \theta_2 x''_0} = \frac{2{\cdot}59 \times 1{\cdot}080}{0{\cdot}455 \times 5{\cdot}89} = 1{\cdot}044.$$

$n = 2$. $\quad K\,(x''_0)^2 = 34{\cdot}67\ K$.

At radius x_3 :

Radial stress $= \sigma_{r3}$:—		f	K
Fig. 4. Coeff. of	$X_2 = J = 1{\cdot}279$	$1{\cdot}2095$	$-29{\cdot}035$
,, 5. ,,	$Y_2 = P = 0{\cdot}355$	$0{\cdot}2902$	$-3{\cdot}804$
,, 6. ,,	$K\,(x''_0)^2 = Q = 0{\cdot}64$		$-22{\cdot}19$
		$1{\cdot}4997$	$-55{\cdot}029$

$= \sigma_{r3}$.

Tangential stress $= \sigma_{t3}$:—		f	K
Fig. 7. Coeff. of	$X_2 = S = 0{\cdot}4925$	$0{\cdot}4658$	$-11{\cdot}19$
,, 8. ,,	$Y_2 = T = 0{\cdot}767$	$0{\cdot}6266$	$-8{\cdot}22$
,, 9. ,,	$K\,(x''_0)^2 = V = 0{\cdot}265$		$-9{\cdot}182$
		$1{\cdot}0924$	$-28{\cdot}592$

$= \sigma_{t3}$.

$K = 289{\cdot}6$.

$\therefore$ At neck :—radius x_3.

Radial stress $\sigma_{r3} = 1{\cdot}4997\,f - 15{,}940$

Tangential stress $\sigma_{t3} = 1{\cdot}0924\,f - 8{,}273$

External load on disc $= L = 352{,}425$ lb.

Area of disc head $= A_r = 3{\cdot}03$ sq. in.

Radius of C. of G. of disc head $= 9{\cdot}465$ in. $= x_4$.

By previous formula :—

$$L = 2\pi A_r \left[\sigma t_3 - K\,(x_4)^2 + \sigma r_3 \left(\frac{y_3\, x_3}{A r} - \right) \right]$$

$\nu =$ Poisson's ratio $= 0{\cdot}3$.

which simplifies to :—

$$44{,}460 = \sigma_{t3} + 1{\cdot}449\,\sigma_{r3}.$$

Inserting in the values of σ_{r3} and σ_{t3} as calculated, gives :—

$$75{,}833 = 3{\cdot}265 f.$$

$\therefore f =$ Tangential stress at hub

$= 23{,}220$ lb. per square inch.

It now becomes fairly simple to calculate the stresses at intermediate points on the disc.

On the parallel-sided portion, for any radius, the cofficients of f and $K\,(x_0)^2$ can be found, and the stresses calculated accordingly.

At radius x'_0 :

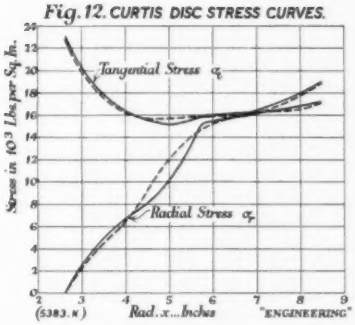
Radial stress $= 0{\cdot}0722\,f - 0{\cdot}6201\ K$

$= 1{,}497$ lb. per sq. in. $= X_1$

Tangential stress $= 0{\cdot}9278\,f - 0{\cdot}1722\ K$

$= 21{,}490$ lb. per sq. in. $= Y_1$

Fig. 12. CURTIS DISC STRESS CURVES.



For intermediate points on the taper portions, a tabulated calculation, given in the opposite Table, facilitates the working, the coefficients of X, Y and $K\,(x_0)^2$ being read from the curves for the values of n required to give the stress curves.

The stresses can be plotted against the corresponding radii and the stress curves drawn, as shown in Fig. 12. The dotted line curves correspond to the stress evaluation by the original "step" method. It will be seen that the curves by both methods are practically identical, the greatest difference being on the curved portion, where the actual stress distribution is of no great importance.

Other advantages of the method are thus apparent :—

(1) The facility of calculation for a new profile should the stresses prove too high in the original disc, and one single calculation starting from the change point of the profile, being only necessary.

(2) The reduction in the possibility of error, as, in the computation of the hub tangential stress, the stresses are calculated at profile change points only, and any error in the first calculation is only multiplied by the number of succeeding profile change points.

(3) No interpolation is required. In the original method, interpolation was generally necessary to obtain the radial and tangential stresses at the neck radius, as the latter was rarely a multiple (either 1·2, 1·1 or 1·05) of the preceding radius.

In conclusion, the author wishes to thank Messrs. The English Electric Company, Limited, for permission to make use of a number of actual turbine disc calculations by which to test the method described in the foregoing article.

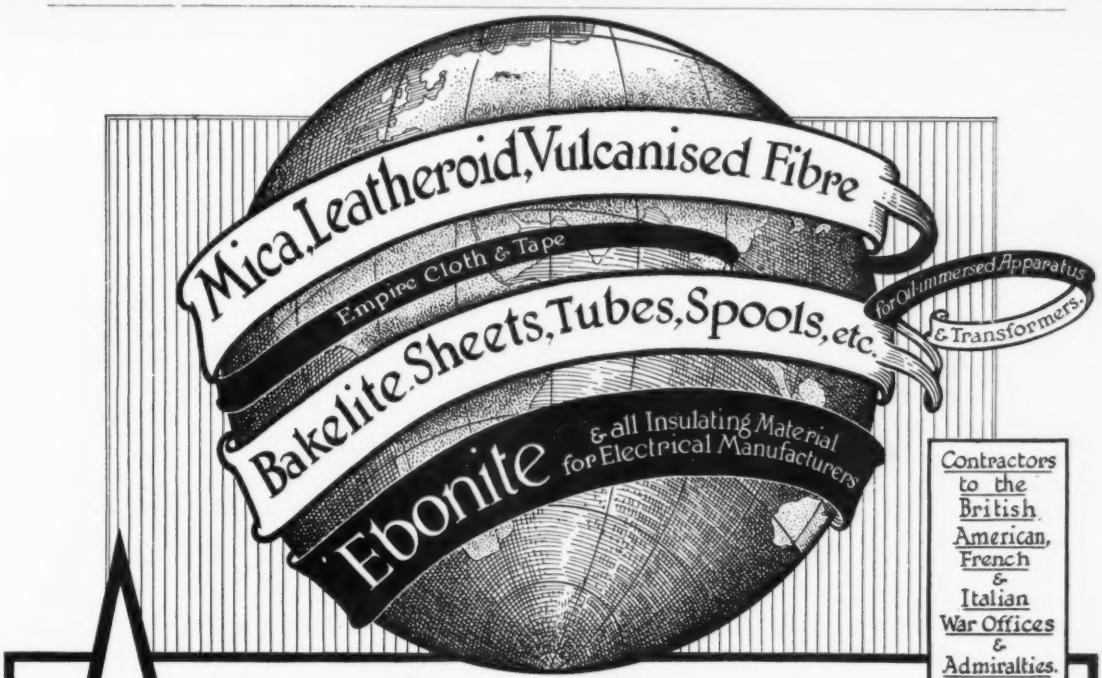
TABLE OF CALCULATIONS FOR INTERMEDIATE POINTS ON TAPER PORTIONS.

Lower Taper — x'_0 to x''_0. $\quad K(x'_0)^2 = 2{,}335.$ $\quad b = 1{\cdot}554.$

$n.$	$x.$	Radial Stress.				Tangential Stress.			
		$X_1.$	$Y_1.$	$K(x'_0)^2.$	Total.	$X_1.$	$Y_1.$	$K(x'_0)^2.$	Total.
1	3·41	0·973 1,457	0·163 3,501	0·22 514	4,444	0·201 301	0·848 18,210	0.08 187	18,324
2	4·09	1·037 1,553	0·31 6,658	0·572 1,335	6,876	0·3875 580	0·7553 16,213	0·24 561	16,232
3	4·91	1·2525 1,875	0·49 10,523	1·195 2,791	9,607	0·605 906	0·7232 15,525	0·54 1,260	15,171
4	5·89	0·9453 f — 22·711 K			15,365	0·8176 f — 10·713 K			15,882

Upper Taper — x''_0 to x_3. $\quad K(x''_0)^2 = 10{,}035.$ $\quad b = 1{\cdot}044.$

$n.$	$x.$	Radial Stress.				Tangential Stress.			
		$X_2.$	$Y_2.$	$K(x''_0)^2.$	Total.	$X_2.$	$Y_2.$	$K(x''_0)^2.$	Total.
1	7·07	1·049 16,112	0·170 2,700	0·231 2,318	16,494	0·230 3,533	0·848 13,460	0·085 853	16,140
2	8·48	1·4997 f — 15,940			18,880	1·0924 f — 8,273			17,107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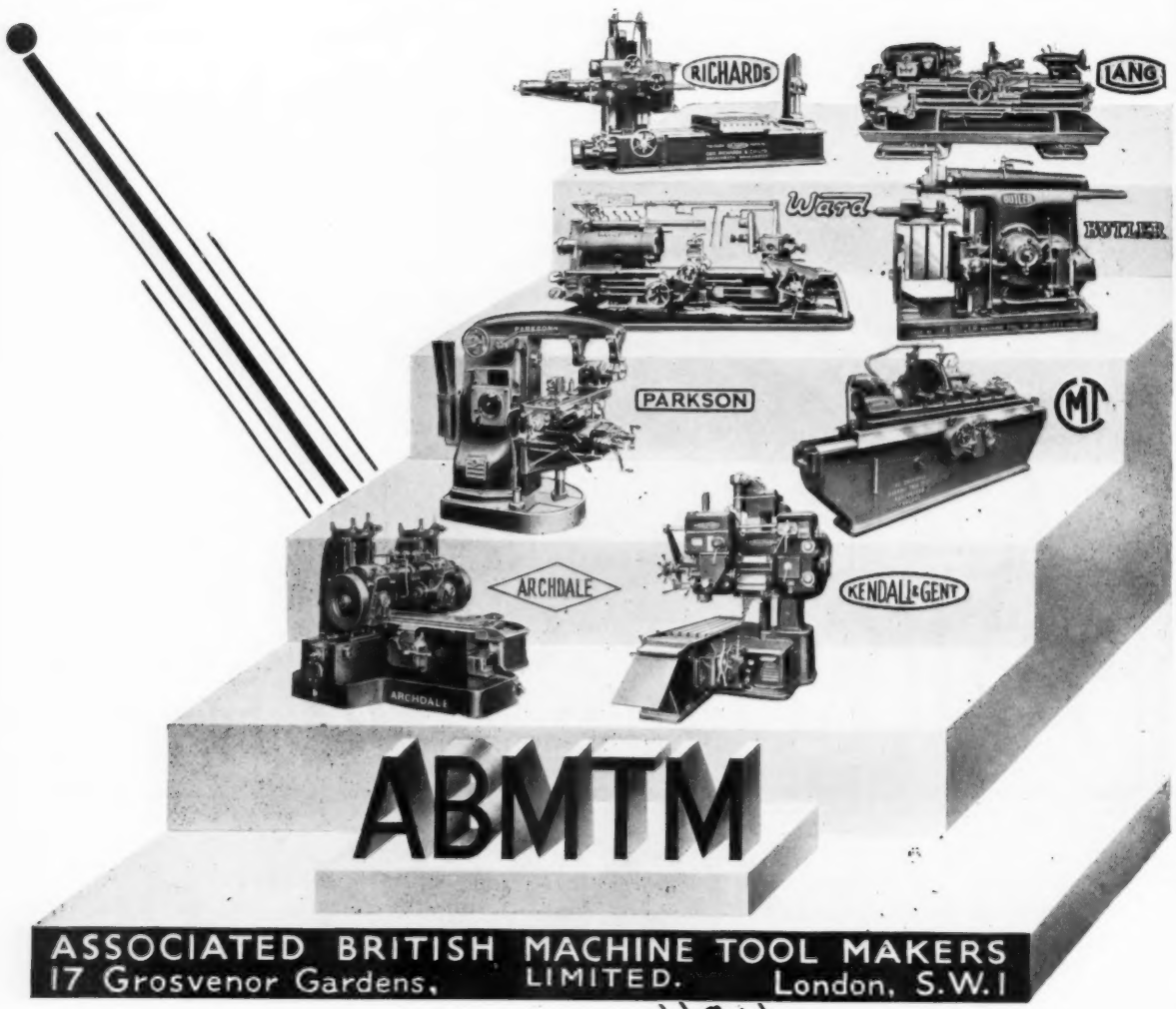

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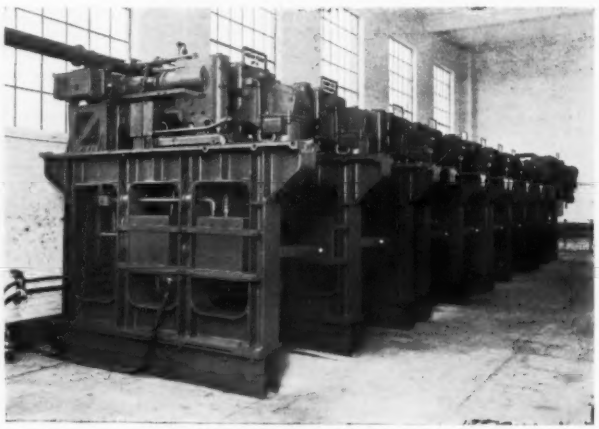

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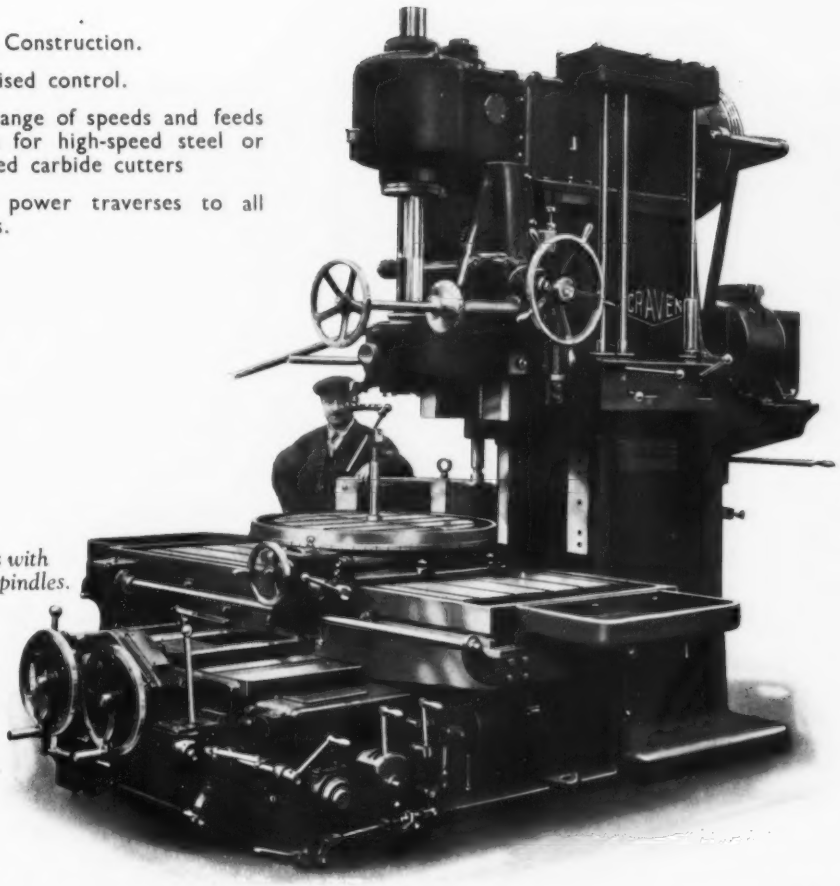

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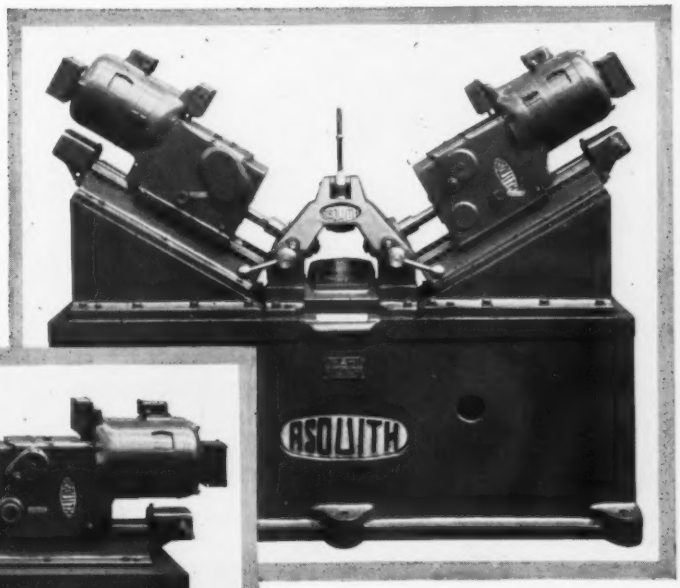

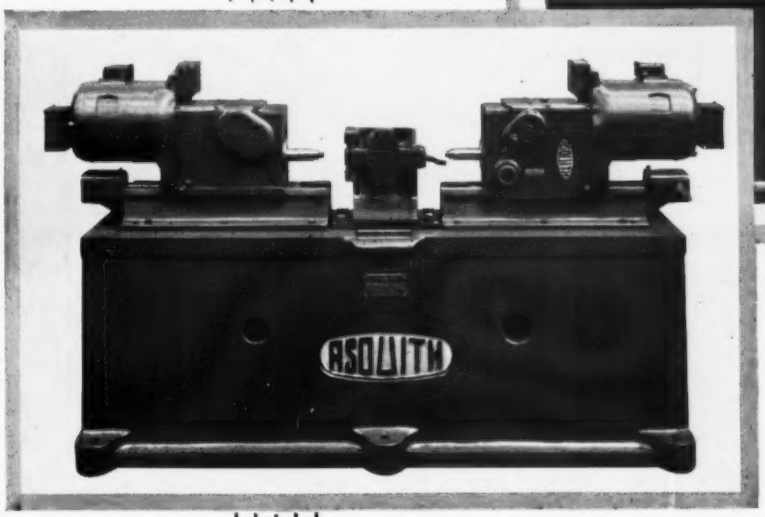

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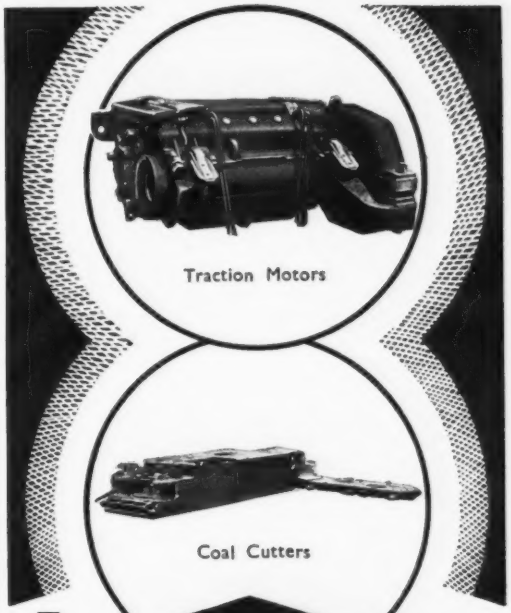

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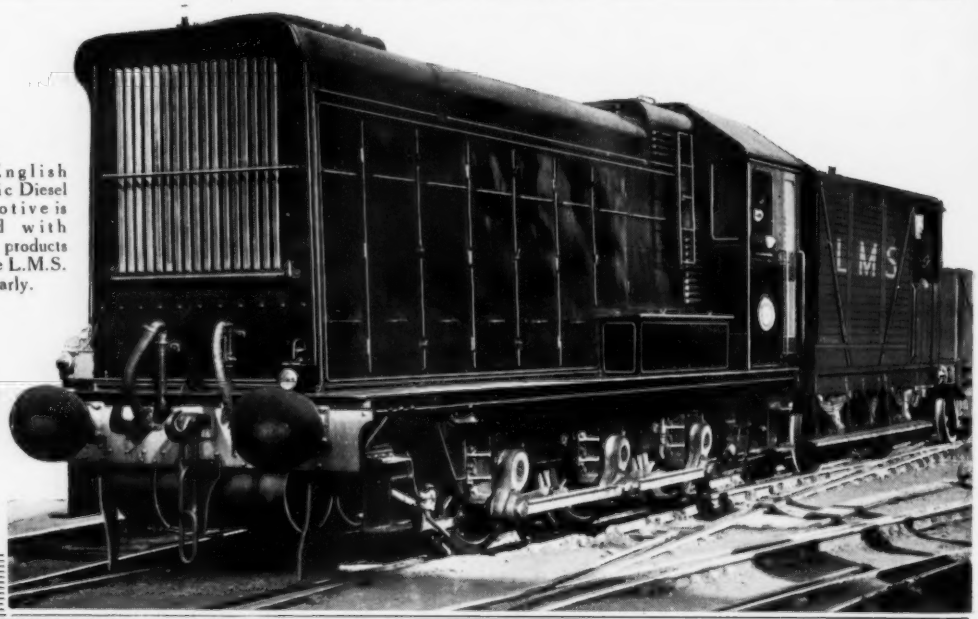

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